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DTU Environment
Department of Environmental Engineering

PhD Thesis
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The synopsis part of this thesis is available as a pdf-file for download from the DTU research database ORBIT: http://www.orbit.dtu.dk

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Preface

This thesis is the outcome of a PhD project carried out at the Department of Environmental Engineering (DTU Environment), Technical University of Denmark in the period from May 2010 to December 2014. The project was supervised by Professor Karsten Arnbjerg-Nielsen (DTU Environment), Professor Henrik Madsen (DHI) and Professor Emeritus Dan Rosbjerg (DTU Environment).

The PhD study was funded by Danish Strategic Research council as a part of the 'Centre for Regional changes in the Earth System' (contract no. 09-066868). Part of the work was carried out with support from the Foundation for Development of Technology in the Danish Water Sector in the project 'Rainfall in a future climate' (contract no. 7492-2012)

This thesis is organized in two parts: The first part puts into context the findings of the PhD study in an introductive review; the second part consists of the papers listed below. These will be referred to in the text by their paper number written with the Roman numerals **I-VI**.

I **Gregersen, I.B**. and Arnbjerg-Nielsen, K. (2012). Decision strategies for handling the uncertainty of future extreme rainfall under the influence of climate change. *Water Science and Technology* **66**(2), 284-291.

II **Gregersen, I.B.,** Sørup, H. J. D., Madsen, H., Rosbjerg, D., Mikkelsen, P. S. and Arnbjerg-Nielsen, K. (2013). Assessing future climatic changes of rainfall extremes at small spatio-temporal scales. *Climatic Change* **118**(3-4), 783-797.

III **Gregersen, I.B.,** Madsen, H., Rosbjerg, D., and Arnbjerg-Nielsen, K. (2013). A spatial and nonstationary model for the frequency of extreme rainfall events. *Water Resources Research* **49**(1), 127-136.

IV Sunyer, M.A., **Gregersen, I.B.**, Madsen, H., Luchner, J., Rosbjerg, D. and Arnbjerg-Nielsen, K. (2014). Comparison of different statistical downscaling methods to estimate changes in hourly extreme precipitation using RCM projections from ENSEMBLES. *International Journal of Climatology*. 15 pages. DOI: 10.1002/joc.4138

V **Gregersen, I.B.,** Madsen, H., Rosbjerg, D. and Arnbjerg-Nielsen, K. (2014). Long term variations of extreme rainfall in Denmark and Southern Sweden. *Climate Dynamics*. 12 pages. DOI: 10.1007/s00382-014-2276-4

VI **Gregersen, I.B.**, Madsen, H., Rosbjerg, D. and Arnbjerg-Nielsen, K. (in prep). A spatial and nonstationary model for Partial Duration Series of rainfall extremes. Manuscript in preparation for *Water Resources Research*

In this online version of the thesis, the articles are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from DTU Environment, Technical University of Denmark, Miljøvej, Building 113, 2800 Kgs. Lyngby, Denmark, reception@env.dtu.dk.

In addition, the following publications, not included in this thesis, were also concluded during this PhD study:

- **Gregersen, I.B**., Arnbjerg-Nielsen, K. and Madsen, H. (2010). Parametric analysis of regional trends in observed extreme rainfall in Denmark. Proc. International Workshop 'Advances in statistical hydrology'. Taormina, Italy. May 2010.
- **Gregersen, I.B**., Arnbjerg-Nielsen, K. and Madsen, H. (2011). Estimation of climate factors for future extreme rainfall: Comparing observations and RCM simulations. Proc. 12th International Conference on Urban Drainage. Porto Alegre, Brazil. September 2011.
- Willems, P., Olsson, J., Arnbjerg-Nielsen, K., Beecham, S., Pathirana, A., **Gregersen, I.B**., Madsen, H., and Nguyen, V.T.V. (2012). "Impacts of Climate Change on Rainfall Extremes and Urban Drainage Systems". IWA Publishing Company.
- Arnbjerg-Nielsen, K., Willems, P., Olsson, J., Beecham, S., Pathirana, A., **Gregersen, I.B**., Madsen, H., and Nguyen, V. T. V. (2013). Impacts of climate change on rainfall extremes and urban drainage systems: a review. *Water Science and Technology* **68**(1), 16-28.
- **Gregersen, I.B.**, Madsen, H., Willems P. and Arnbjerg-Nielsen, K. (2014). Implications of long term oscillations in precipitation extremes on urban drainage design practices. Proc. 13th International Conference on Urban Drainage. Sarawak, Malaysia. September 2014.
- **Gregersen, IB**, Madsen, H, Linde, JJ and Arnbjerg-Nielsen, K (2014). Klimafaktorer og dimensionsgivende regnintensiteter: Skrift nr.30. IDA Spildevandskomiteen.
- **Gregersen, IB**, Sunyer Pinya, MA, Madsen, H, Funder, S, Luchner, J, Rosbjerg, D & Arnbjerg-Nielsen, K (2014). Past, present, and future variations of extreme precipitation in Denmark: Technical report. DTU Environment, Kgs. Lyngby.
- Sunyer, M.A., **Gregersen, I.B.**, Madsen, H., Rosbjerg, D. and Arnbjerg-Nielsen, K. (2014). Extreme precipitation in a future climate – assessing climate factors at sub-daily scales from Regional Climate Model projections. Proc. 13th International Conference on Urban Drainage. Sarawak, Malaysia. September 2014.
- Madsen, H, **Gregersen, IB**, Arnbjerg-Nielsen, K, (in prep.) Regional frequency analysis of short duration rainfall extremes in Denmark from 1979-2012. *Atmospheric research*

Acknowledgements

This PhD study was carried out as a part of 'Centre for Regional changes in the Earth System" supported by the Danish Strategic Research council. Our project meetings have provided the opportunity for many scientific discussions in a social atmosphere. So has the project 'Rainfall in a future climate' supported by the Foundation for Development of Technology in the Danish Water Sector. During this project I got a unique opportunity to apply some of my research for urban drainage guidelines in cooperation with the end users and my supervisors. Additionally, I was lucky to be a part of the steering group for the rain gauge network of the Danish Water Pollution Committee (In Danish Spildevandskomiteens regnmålernetværk); a network that has provided me with the most fundamental data for my research.

I have truly enjoyed working at DTU Environment and thank the 'Climate Change Impacts and Adaptation' research group and the UrbanWaterTech PhD School for inspiring meetings and social activities. I have had many nice colleagues both in the administrative and scientific staff, and some very lovely office mates (Annette, Qianqian, Maria, Hjalte, Helena, Nina and Roland) to share coffee and the joy and frustration of the PhD study with. I thank my supervisors (Karsten Arnbjerg-Nielsen, Henrik Madsen and Dan Rosbjerg) for inspiration, support and our shared passion for extreme rainfall statistics. It has been a pleasure working with you.

I am grateful to my family and friends, especially Andreas, for support and encouragement and just for being a part of my life. Clara has only been around for the last part of the PhD, but she has still taught me more than anyone else.

Summary

A well-functioning drainage system is of utmost importance to ensure safe and liveable cities. The cost of urban flooding is high and in worst case fatal. Denmark has a long tradition for providing guidelines for urban drainage design, including recommendations on design rainfall. A regional model for estimation of urban design intensities has been applied since 1999. The main motivation is that the uncertainty of the estimated design intensities can be reduced by including regional information. The model has been updated several times, but its basic assumptions are now challenged by several indications of non-stationary extreme rainfall behaviour, in Denmark as well as worldwide.

To provide recommendations on future design intensities it is necessary to explore and understand patterns of temporal variation in urban design rainfall and identify potential drivers behind past, present and future changes. In addition, there is a need for an extreme value model that can include both regional and temporal explanatory variables, evaluate their significance and on this basis estimate the design rainfall. Both topics are addressed in this thesis. The analysed data material includes 137 years of observed daily rainfall, and 34 years of high-resolution observations from a regional tipping-bucket network. To evaluate future design intensities climate model simulations from the ENSEMBLES project is applied, in combination with two high-end simulations.

The number of extreme rainfall events and the mean intensity of sub-daily extreme rainfall have increased over the last 34 years. Analysis of the long daily rainfall series show that the number of extreme rainfall events, smoothed by a 10-year moving average, fluctuates between periods of relative high and periods of relatively low number of extremes. The increase observed over the last 34 years fits well into this pattern. Sea level pressure differences over the North Atlantic are found to be a potential driver of this multi-decadal variability. Specific constellations of high and low pressure zones favour a high number of extreme rainfall events in Denmark, and these form more frequently in some decades. In relation to the increase in mean intensity of sub-daily extreme rainfall, sea surface temperature of the Danish waters is a strong candidate among the potential drivers. The correlation between the two is not studied in detail in this thesis.

In relation to projections of future rainfall extremes anthropogenic climate change plays an important role. At higher temperatures the air can hold more water and therefore release more rainfall. Climate change can also affect the variability of the extreme rainfall indirectly by a modification or intensification of the large scale drivers. Climate models are the most important tool for assessing the magnitude of the change, but their output should be critically assessed especially in regard to extreme rainfall. The thesis shows that the spatial correlation structure of observed hourly extreme rainfall is not reproduced well by the two climate models assessed.

The thesis also presents a framework in which regional and temporal variability of extreme rainfall statistics can be modelled simultaneously. The framework is an extension of the regional model presently used for estimation of urban design intensities. It applies a threshold value for extreme rainfall that varies in both time and space. This eliminates the issue of having a non-uniform distribution of extremes events over the observation period. Furthermore, the model is capable of taking the spatial correlation structure of the rainfall extremes into account. The model can compare the relative importance of the temporal and regional variation. For several of the analysed rainfall durations regional variation is identified, but temporal variability explains a larger percentage of the total variability. The presented model only includes 'time' as a temporal variable. It can be modified to contain physical explanatory variable, like the two large scale drivers discussed above, when their present and future influence is confirmed.

The analysed climate model simulations show that over the next 100 years the most likely increase of a 2-year event with a rainfall duration of 1 hour is 20 %. This almost corresponds to the change observed over the last 34 years, which emphasises the importance of understanding the large scale drivers behind.

It is very important to quantify and communicate the uncertainty of the design rainfall both in relation to the natural variability, the expected impacts of climate change and their interplay. A large part of the uncertainty is inherent and cannot be reduced. On top of this come the many unknown features in the climate system. The irrational behaviour of mankind contributes to the uncertainty, as it both affects the greenhouse gas emissions, and the requirements to cities of the future. Simple case studies based on different decision making frameworks show that the uncertainty of the future is not a hindrance for adaptation.

Dansk sammenfatning

Velfungerende afløbssystemer er helt fundamentale for vores byer og deres udvikling. Omkostningerne ved urbane oversvømmelser er høje og tæller i værste fald menneskeliv. I Danmark har vi gennem en lang årrække haft nationale retningslinjer for design af afløbssystemer, herunder en rekommandation vedrørende dimensionsgivende intensiteter. Anbefalingen er, at disse estimeres ud fra en regional model for ekstremregn. Denne blev indført i 1999, da usikkerheden på estimatet af de dimensionsgivende intensiteter kan reduceres ved inkludering af regional information. Modellen er blevet opdateret to gange gennem det sidste årti, men i dag stilles der spørgsmål ved en af modellens vigtige antagelser. Dette skyldes en tydelig indikation af, at ekstremregn ikke længere kan anses som stationær. Denne tendens ses både i Danmark og i andre del af verden.

For fortsat at kunne fremsætte nationale anbefalinger af dimensionsgivende intensiteter er det nødvendigt at vurdere ekstremregnens udvikling over tid, samt mulige fysiske drivkræfter bag den fortidige, nutidige og fremtidige udvikling. Der er ydermere behov for en regional ekstremregnsmodel, der tager højde for den tidslige udvikling, således at forklarende variable kan inkluderes for både tid og sted. Modellen skal kunne vurdere den statistiske signifikans af de forklarende variable, samt estimere dimensionsgivende intensiteter på basis af disse. Denne afhandling bidrager til løsningen af ovenstående problemstilling. Det analyserede datamateriale omfatter 137 års lange regn serier med daglige målinger og 34 års data i høj opløsning fra et regionalt netværk af vippekarmålere. Endvidere anvendes klimamodelsimuleringer fra det europæiske ENSEMBLES projekt kombineret med to simuleringer drevet af høje emissionsscenarier til analyser af fremtidens dimensionsgivende regn.

De sidste 34 år er både antallet af ekstreme regnhændelser samt middelintensiteten af den ekstreme regn under én dags varighed steget. Analysen af de lange, daglige regn serier viser, at antallet af ekstreme regnhændelser, udglattet med et 10-års glidende gennemsnit, svinger mellem perioder med relative mange og relativt få ekstreme hændelser. Den omtalte stigning, over de seneste 34 år, er i overensstemmelse med dette mønster. Forskelle i lufttryk over Nord Atlanten er en potentiel drivkraft bag det observerede mønster. Specielle høj- og lavtryks konstellationer synes at fremme antallet af ekstreme regnhændelser i Danmark, og disse dannes hyppigere i nogle årtier end i andre. I forhold til stigningen i middelintensiteten af den ekstreme regn under én dags varighed er temperaturen i de danske farvande en stærk kandidat blandt de potentielle drivkræfter. Korrelation er ikke analyseret direkte i nærværende afhandling.

Den fremtidige ekstremregn vil unægteligt blive påvirket af de menneskeskabte klimaændringer. Først og fremmest stiger luftens potentielle vandindhold med temperaturen og dermed den potentielle regnintensitet. Klimaændringerne kan også have en indirekte virkning, hvis de tidligere nævnte drivkræfter modificeres eller intensiveres. Klimamodeller er det bedste værktøj til at vurdere potentielle ændringer i fremtidens ekstremregn, men man bør forholde sig kritisk til resultaterne, især den simulerede ekstremregn. F.eks. viser afhandlingen, at to udvalgte klimamodeller ikke er i stand til at gengive den spatiale korrelationsstruktur, som kendetegner observeret ekstremregn.

Afhandlingen præsenterer endvidere en metode til modellering af ekstremregnens statistiske karakteristika i tid og sted. Metoden er en videreudvikling af den nuværende regionale ekstremregnsmodel. Den anvender en tærskelværdi for ekstremregn, der varierer over tid og sted. Med denne udgås den skrævvridning, der ellers opstår, når de ekstreme hændelser ikke er ligeligt fordelt over observationsperioden. Endvidere kan modellen tage ekstremregnens spatiale korrelationsstruktur i regning. Modellen muliggør en sammenligning mellem størrelsesordenen af henholdsvis regional og tidslig variation. Denne viser, at den regionale variation har betydning, men at udviklingen over tid kan forklare langt den største del af den total variabilitet. Konklusionen afhænger af dog af ekstremregnens varighed. Den foreslåede model for de dimensionsgivende regnintensiteter benytter kun ’tid’ som forklarende variable. Modellen kan også inddrage de før omtalte fysiske drivkræfter i det tidslige domæne, når deres nutidige og fremtidige indflydelse er bekræftet.

Ud fra de analyserede klimamodelsimuleringer er det bedste bud på ændringen af en 2-års hændelse en stigning på 20 % over en tidshorisont på 100 år. Dette svarer omtrent til den ændring, der allerede har fundet sted over de sidst 34 år, hvilket tydeliggør behovet for at forstå de fysiske drivkræfter bag.

Der er et stort behov for at kvantificere og kommunikere usikkerheden på den dimensionsgivende nedbør, både i forhold til den naturlige variabilitet, de menneskabte klimaændringer og interaktionen mellem de to. En stor del af usikkerheden er iboende og kan ikke mindskes. Derudover er der mange ukendte mekanismer i klimasystemet. Den menneskelige adfærd bidrager hertil ved at være uforudsigelig og irrationel, hvilket både har indflydelse på den fremtidige emission af drivhusgasser og kravet til fremtidens byer. Gennem simple eksempler baseret på forskellige beslutningsteorier vises det, at usikkerheden omkring fremtidens dimensionsgivende intensiteter ikke bør være en hindring for klimatilpasning.

Table of contents

Abbreviations

CF	Climate Factor
DMI	Danish Metrological Institute
EA	East Atlantic pattern
ENSO	El-Niño Southern Oscillation
GCM	Global Climate Model
GEE	Generalized Estimation Equations
GHG	Greenhouse Gasses
GLM	Generalized Linear Models
GLMGEE	Generalized Linear Models solved by Generalized Estimation Equations
GLS	Generalized Least Squares
GPD	Generalized Pareto Distribution
IDF	Intensity-Duration-Frequency
IPCC	Intergovernmental Panel on Climate Change
NAO	North Atlantic Oscillation
NOAA	National Oceanic and Atmospheric Administration
MAP	Mean Annual Precipitation
MSPL	Mean Sea Level Pressure
MSPLD	Mean Sea Level Pressure differences
OLS	Ordinary Least Squares
PCA	Principle Component Analysis
PDS	Partial Duration Series
POT	Peak Over Threshold
RCM	Regional Climate Model
SLPD	Sea Level Pressure Differences
SNAO	Summer North Atlantic Oscillation
SST	Sea Surface Temperature
SVK	Spildevandskomitten
WPC	the Danish Water Pollution Committee

1 Introduction

1.1 Urban drainage and design rainfall

The first sewer systems were built in the middle of the 19th century to transport grey-water and storm water out of the cities. The increased focus on controlling the flows of water in and out of the city, and thereby ensuring a clean drinking water supply, was strongly motivated by the cholera epidemics racking Europe in the previous decades (Butler and Davies 2011; Winther et al. 2006). The sewer systems were regarded as a keystone in city development, as they increased the hygienic level in the cities tremendously. As flush toilets became increasingly common, the sewer system was designed also to receive their effluent.

Comparing the magnitude of the different contributions to the total water flow in a combined sewer system during a heavy rainfall event, the grey and black household wastewater constitute less than 5% (Winther et al. 2006). The cost of construction is therefore highly dependence on the expected rainfall intensities and knowledge on these is essential for design of the sewer system. The required temporal resolution of the rainfall data, which is depending on the size of the catchment covered by the urban drainage system, was below one hour for all Danish cities in the beginning of the 20th century. In 1928 investigations by the Town and Harbour Engineering Administration concluded that the daily rainfall series provided by Danish Meteorological Institute (DMI) were inadequate for sewer design (WPC 1950). In 1933 they, therefore, installed high-resolution rain gauge in six of the major Danish cities providing rainfall measurements with a temporal resolution of five minutes.

The pollution of receiving waters and the need of mechanical wastewater treatment were recognised already in the beginning of the 20th century, but became evident as the number of flush toilets increased (WPC 1949). The need of recommendations for pollution control measures triggered the formation of Spildevandskomiteen (SVK), in English the Water Pollution Committee of The Society of Danish Engineers (WPC) in 1944.

During 1940-50 a large number of retention basins were built for temporary storage of large rainwater volumes, reducing the combined sewer overflows of untreated wastewater to surface waters during rain events. With this, the complexity of the sewer system increased. For estimation of storage volumes, design intensities with durations of up to several days were needed. In large systems with many basins, knowledge on coupled rainfall events, which add additional rainfall volumes before the already utilized storage volumes are emptied, also became important. However, it was first in the 1990s, after a decade of advances within computer modelling, that the sewers from an engineering point of view were modelled as part of a larger system. The most common term today is not sewers but urban drainage systems, to emphasize the service provided to society rather than a specific means or technology. The main part of the system is still pipes, gully pots and manholes, which have a high renewal cost and a technical lifetime of 70-100 years (Winther et al. 2006).

Integrated system analysis often includes cross-disciplinary interactions, see Figure 1.1. City development is dynamic and depends on many factors, which indirectly interacts with the service provided by the urban infrastructure. A house with a creek in the backyard often has a high market value, because the creek is perceived as an asset. However, this will suddenly change when the creek floods the house, and if this happens several times (see **Paper I**) the marked value of the house will decrease rapidly. The probability of flooding depends on the climate and the urban infrastructure. Both are changing over time, together with many of the other features in Figure 1.1.

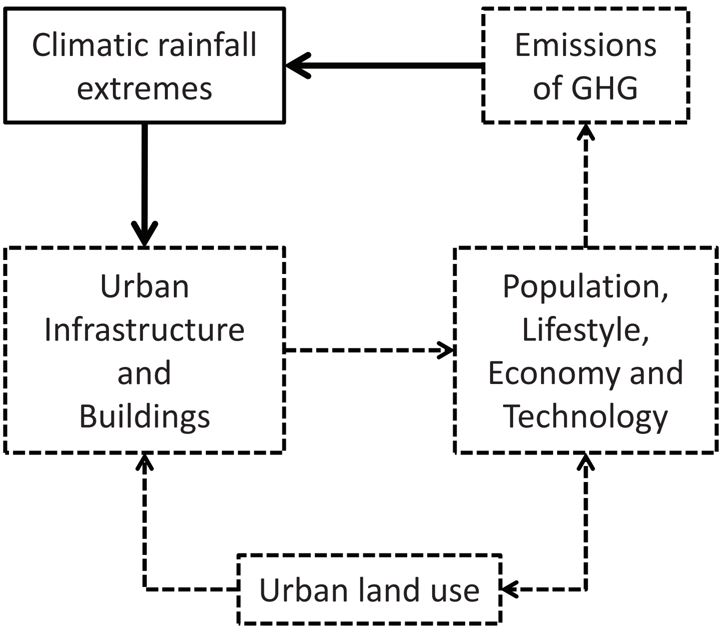

Figure 1.1: Sketch of conceptual relationships in urban drainage design, focusing on the climatic rainfall extremes. GHG: Greenhouse gases. Source: **Paper I.**

Bottom line is that a system, which is not designed correctly according to the rainfall extremes, will fail to provide the level of service that the inhabitants of the city rely on.

The first recommendations on design intensities in Denmark were the second and sixth publications from WPC (WPC 1950; 1953). The intensities were estimated from the six rain gauges, but have been updated several times since then. First in 1974, still based on measurements from the six pluviometers but with a longer period of observation (WPC 1974), and later in 1999, 2006 and 2014, based on a dense regional network of tipping-bucket gauges, which was established in 1979 (WPC 1999; 2006; 2014). In the remainder of the thesis this network is named SVK, from the Danish abbreviation of WPC. The new information provided by the SVK network, combined with national advances within the area of extreme value modelling, enabled an assessment of regional differences in design intensities over Denmark. The model introduced in 1999 is still considered state-of-the art within the field of extreme rainfall analysis Madsen et al. (2002).

As the increasing publication frequency of updated guidelines shows, there has been a strong demand for repeated analysis of the rainfall measurements with additional years of observation. The driver is a compelling amount of evidence suggesting that the climate is non-stationary and that the design intensities therefore change over time. In the last two decades quite a dramatic increase in extreme precipitation has been observed, resulting in numerous pluvial floods in Denmark. During these floods the capacity of the drainage systems has been exceeded, leading to extensive property and infrastructure damage, and thus high economic costs. On top of this comes the ongoing discussion on future climatic changes driven by the anthropogenic emissions of greenhouse gases (GHG). The most recent report from the Intergovernmental Panel on Climate Change (IPCC) states that forthcoming changes of the climate are unequivocal (IPCC 2013). There is strong theoretical evidence that the frequency and/or intensity of extreme rainfall events will increase with the mean global temperature (Westra et al. 2014). The magnitude of the change is very uncertain, but the associated cost of repeated urban floods is known to be very high (Arnbjerg-Nielsen and Fleischer 2009).

In addition to protection from floods, the drainage system still serves the utmost purpose of protecting the populations against chemical pollution and waterborne diseases. A well-functioning urban drainage system that can be adapted to present and future climatic changes is therefore crucial, and a cornerstone in maintaining such a system is knowledge on the temporal variations of the extreme rainfall events the system should be designed to handle.

1.2 Research objectives

The PhD study has focused specifically on the area of Figure 1.1 framed by solid lines, i.e. the climatic rainfall extremes, together with their drivers, and the indirect implication on urban infrastructure, see Figure 1.2. Statistical models are an essential tool for describing the spatio-temporal variability of the climatic rainfall extremes. They are used to assess the relationship to underlying physical drivers of variability and for estimation of design intensities.

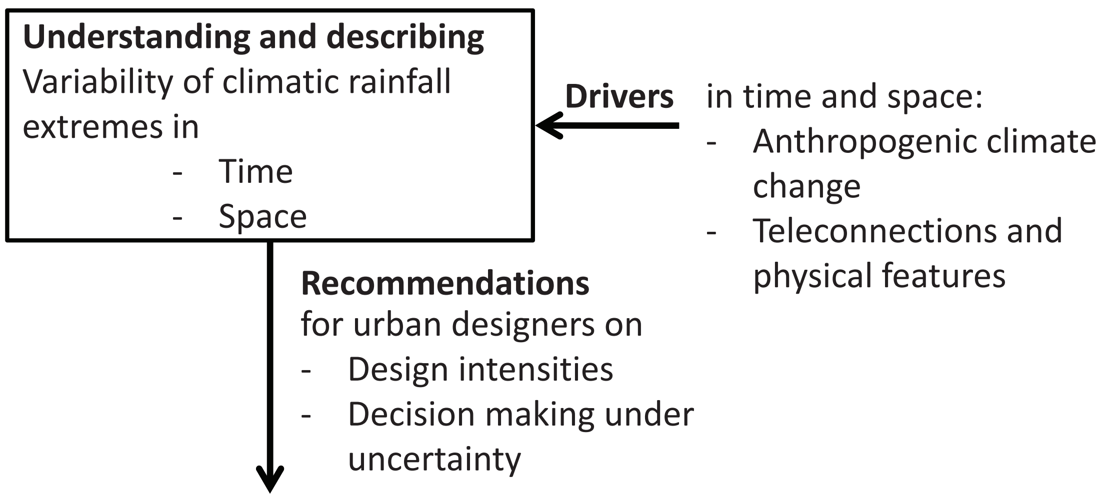

Figure 1.2: Essential aspects of modelling climate rainfall extremes in the framework of urban drainage design.

As mentioned in Section 1.1 there is a long Danish tradition of using the WPC publications as national guidelines for urban drainage design. The regional variability of extreme rainfall was at the beginning of the PhD study described by a statistical model and implemented in a spreadsheet for practical use (WPC 1999; 2006). The gap in knowledge is evident with regard to the non-stationarity of our climate system and its impact on design rainfall. The increase in design intensities observed since 1979, where the Danish tipping-bucked network was established, must be evaluated. This should include a comparison to variations in the past and the expected impacts of anthropogenic climate change. For this non-stationary time series models of extremes are required. The developed models should preferably be compatible with, or be able to replace, the regional model for variation of design intensities.

Finally, the impact on current practice, as well as possible needs for change, must be considered.

On this basis the PhD study has consisted of the following parts:

1) Explore and understand patterns of regional and temporal variation in urban design rainfall and potential drivers behind past, present and future changes.
2) Develop extreme value models that can include both regional and temporal explanatory variables, evaluate their significance and on this basis estimate urban design intensities.
3) Make guidelines and frameworks for urban drainage engineers based on the two previous bullet points.

Table 1.1 shows the papers included in the thesis and to which research aspects they contribute. Furthermore, Table 1.1 highlights areas where the thesis provides a larger perspective based on additional research not covered by the included papers.

Table 1.1: Papers included in the thesis, classified according to the different aspects considered for modelling climate rainfall extremes (in columns), see Figure 1.2 - combined with the three main chapters of the thesis (in rows).

<table>
<tr><th rowspan="2"></th><th colspan="2">Temporal variation</th><th>Regional variation</th><th rowspan="2">Design intensities and decision making</th></tr>
<tr><th>Teleconnections</th><th colspan="2">Climate change and climate models</th></tr>
<tr><td>Drivers of rainfall variability</td><td>Thesis
Paper III
Paper V</td><td colspan="2">Paper II</td><td></td></tr>
<tr><td>Statistical modelling of variations in extreme rainfall</td><td colspan="3">Paper II
Paper III
Paper V
Paper VI</td><td></td></tr>
<tr><td>Variations of design rainfall in Denmark</td><td></td><td colspan="2">Paper II
Paper IV</td><td>Thesis
Paper I
Paper IV
Paper VI</td></tr>
</table>

The thesis is structured as follows: Section 2 presents the different datasets used in the PhD study. Section 3 briefly reviews the rainfall process and the drivers of variability in extreme rainfall. Results from the PhD study regarding potential drivers are highlighted. Section 4 presents extreme value theory for variations in space and time. The regional model applied presently is introduced briefly, followed by the developed and applied extensions, which focus on temporal variability. Section 5 presents all results regarding extreme rainfall variability in Denmark and discusses the findings relevant for present and future guidelines on design intensities. The conclusion is given in Section 6, and finally suggestions for future research are given in Section 7.

2 Data

For analysis of extreme rainfall variability in Denmark, two different datasets of observed rainfall, and a range of climate model simulations, are available. The analysed rainfall data is described briefly in this section.

2.1 Rain gauge observations

Observations from rain gauges are used to analyse the long-term (**Paper V**) and recent (**Paper II, III** and **IV**) variations of design rainfall. Table 2.1 gives an overview of the available datasets. The datasets from SVK and DMI are thoroughly quality controlled. For the SVK and DMI network the procedures are described by Jørgensen et al. (1998) and Lundholm and Cappelen (2010), respectively. For the long DMI series the homogeneity has been confirmed by double mass curves. None of the datasets are corrected for the wind-induced under-catch or the wetting and evaporation loss as the percent-wise effect is known to be small for the extreme intensities (Nielsen and Cappelen 2006). However, changes in the shelter index of a gauge can introduce a non-stationary behaviour in the observed extreme rainfall (Jørgensen et al. 1998). There is not enough information available to consistently correct all SVK series according to the shelter-index. Madsen et al. (2002) tested the impact of the shelter-index on the regional variations of extreme precipitation and found it non-significant.

Table 2.1: List of analysed rain gauge observations.

Dataset	Resolution	Period of observation	Number of stations	Station years in total	Paper
SVK network	0.2mm/min	1979-2012	83	1881	II, III, IV, VI
DMI long records	0.1mm/day	1874-2010	5	676	V
DMI network	0.1mm/day	1961-2010	56	2735	V
SMHI long records	0.1mm/day	1874-2010	7	670	V

Notice that in Paper II and III a smaller selection of the SVK data has been analysed, only including observations up to 2009. SMHI refers to the Swedish Meteorological and Hydrological Institute.

2.2 Climate model simulations

Simulated precipitation from Regional Climate Models (RCMs) is analysed both for the present and the future. The purpose is to evaluate the possible magnitude of change in design intensities for urban drainage (**Paper IV**), but also to critically assess the data available for this purpose (**Paper II**). All model simulations listed in Table 2.2 are simulated as part of the European ENSEMBLES project (van der Linden et al. 2009). RCMs receive lateral boundary conditions from Global Climate Models (GCMs) or from re-analysis data. The GCMs are forced by observed GHG concentrations in the atmosphere until year 2000 and thereafter by concentrations corresponding to the A1B scenario (IPCC 2000). The analysed RCM data has a spatial resolution of 25 km and simulations for the period 1950-2100, except when driven by re-analyses data, where the simulation period is 1958-2002.

Table 2.2: List of analysed climate model simulations.

RCM	GCM/*re-analysis*	Data resolution	Paper
HIRHAM5	ARPEGE	1 hour max, daily	IV
HIRHAM5	**ECHAM5**	1 hour, 1 hour max, daily	II, IV
HIRHAM5	BCM	1 hour max, daily	IV
REMO	ECHAM5	1 hour max, daily	IV
RACMO2	**ECHAM5**	1 hour, 1 hour max, daily	II, IV
RACMO2	***ERA40***	1 hour	II
RCA	ECHAM5	1 hour max, daily	IV
RCA	BCM	1 hour max, daily	IV
RCA	HadCM3Q3	1 hour max, daily	IV
CLM	HadCM3Q0	1 hour max, daily	IV
HadRM3Q0	HadCM3Q0	1 hour max, daily	IV
HadRM3Q3	HadCM3Q3	1 hour max, daily	IV
HadRM3Q16	HadCM3Q16	1 hour max, daily	IV
RCA3	HadCM3Q13	1 hour max, daily	IV

Most of the models provide data at daily resolution. The variable ‘1 hour max’ is the maximum hourly precipitation intensity for a given day. For three of the simulations data with a resolution of one hour have been acquired (marked by bold), one of these is driven by re-analysis data (marked by italic).

3 Drivers of rainfall variability

An understanding of the regional and temporal variations of design intensities requires knowledge on the physics of the precipitation process. The scale of these processes ranges from the size of the grain on which atmospheric moisture condensates to hundred thousands of square kilometres covered by the large scale meteorological mechanisms known as teleconnections. In the context of extreme rainfall and urban drainage system, this section briefly reviews the different rainfall mechanisms. Hereafter, known regional and temporal variations are reviewed and the contribution of the PhD study is highlighted. The temporal variability comprises the expected impact of climatic changes, which also builds on a physical understanding of the climate system.

3.1 Rainfall mechanisms

Formation of droplets in the atmosphere requires moist air and a nucleus for condensation. Air parcels reach the dew point by cooling, which often is accommodated by vertical uplift. Different mechanisms can initiate this process, and the resulting rainfall is often classified according to the underlying mechanism. In the following convective rainfall, frontal rain along a warm front, frontal rain along a cold front and rainfall generated by the orographic effect are considered.

Convective clouds are created when local air parcels becomes warmer than the surrounding air and rises. Depending on the rate of uplift and the moisture content of the rising air, this can lead to high intensity rainfall (Dingman 1994). Convective rainfall is often both local and changeable leading to high differences in the rainfall intensity over time and space. The spatial extent of a convective rain cell is in the range from 1 to 10 km^2 and the life time of such a cell is rarely longer than 30 minutes (Austin & Houze 1972). Therefore, convective rainfall storms are associated with short duration rainfall extremes that vary in space, potentially leading to quite different registrations of rainfall intensity even at neighbouring sites.

A front is defined as an air mass boundary along which temperature and pressure gradients are relatively large (Dingman 1994). Cyclonic storms circulating around a centre of low pressure are formed along this frontal boundary. They consist of both a warm and a cold front (see Figure 3.1). When a moving warm front meets cold air, which has a higher density, the air parcels in the warm front is lifted creating low or medium rainfall intensities over a large area (Dingman 1994). The width of a moving front is in the range from

50 to 100 km, while the lifetime is several days (Austin & Houze 1972). The average wind speed of a moving front is around 10 m/s (Niemczynowicz 1988). Rainfall along a warm front can contain elements of convective precipitation. A cold front follows the warm front (see Figure 3.1). When a moving cold front meets warm air, the air parcels ahead are forced radically upwards creating relatively high rainfall intensities covering a more limited area (Dingman 1994).

Uplift can also be generated by topography, a process known as the orographic effect. This effect is most pronounced in mountainous areas, but in Denmark a ridge through Jutland, formed during the late ice age, is known to affect the regional variation of the mean annual precipitation (MAP) (Frich et al. 1997), as well as many other statistics.

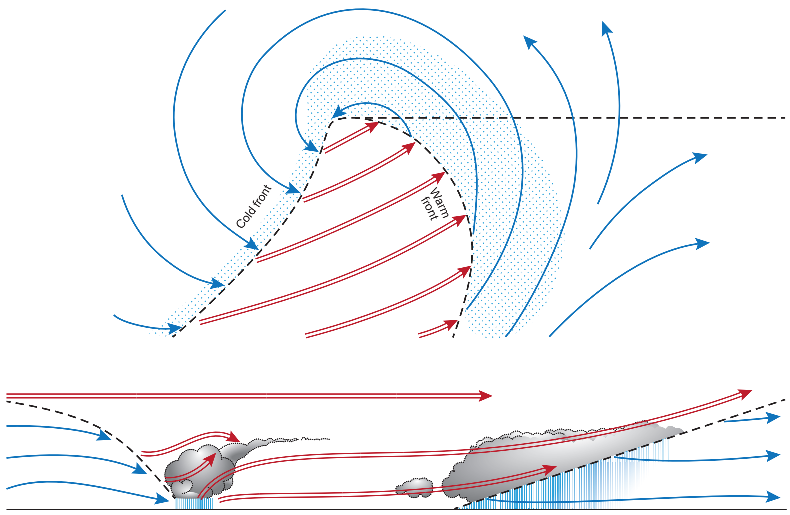

Figure 3.1: The moving warm and cold front in a cyclonic storm seen from above (top) and along a vertical cross-section (bottom). Source: Modified from WPC (1984).

In reality, the actual rainfall mechanisms are far more complicated than reviewed above, and the rainfall intensity depends on several other factors; i.e. the temperature difference between the two air masses, the wind speed, the extent of the cold front and the supply of new moist air.

With this in mind, the difference in lifetime and physical extent between convective and frontal rainfall creates very distinctive spatial characteristics. As a very rough guideline, short duration (<1hour) design intensities often occur from convective activity, while long duration design intensities (>1day) often occur from frontal activity. For durations in between we expect a mixture of the two mechanisms.

The outlined rainfall mechanism implies that the probability of rain and the intensity of the event can be forecasted under different scenarios, but not without uncertainty. Parts of the rainfall mechanisms are chaotic and the resulting uncertainty is inherent. Rainfall statistics can also be related to physical properties, which vary regionally or over time, but the inherent uncertainty prevails, and is particularly high for the extreme value statistics. The two following sections describe regional or temporal conditions, which can enhance the probability of observing extreme rainfall.

3.2 Regional variation of extreme point rainfall in Denmark

Denmark lies approximately at the 55^{o} latitude in the Northern Hemisphere on the border between the North Sea and the European continent. The variability of rainfall over the country is therefore dominated by the proximity of a transition zone for latitudinal atmospheric circulation (Dingman 1994). The predominant wind direction is from west to east which, depending on the storm tracks and the location of the Polar Jet Stream, brings frontal systems in from the North Sea. The climate in western Jutland is coastal and changeable, while the climate in the eastern part of Denmark resembles more the climate of the continent.

For specific storm track directions, the rainfall in the most northern part of Jutland may be influenced by the shelter from Norwegian mountains. In combination with the impact of the Jutlandic Ridge mentioned in Section 3.1, this leads to MAP intensities of 800-1000 mm in the south-western and central part of Jutland and intensities of 500-800 mm in the rest of the country (Frich et al. 1997). A southern or eastern wind direction will bring air from the continent, which in combination with the warm waters from the Baltic Sea can create good conditions for thunderstorms and convective showers (Cappelen 2013; Frich et al. 1997).

It is expected that the physical characteristics described above will influence the regional variation of the design intensities. The variation might differ for different rainfall durations as a consequence of the underlying rainfall mechanism. The regional variation has been the topic of three WPC publications (WPC 1999; 2006; 2014). The understanding of the regional variability has increased with the amount of available data, but patterns are still observed that cannot be related to physical characteristics. Madsen et al. (2002, 2009, in prep.) consistently showed that the frequency of extreme rainfall events is positively correlated to the regional variation of MAP. The mean extreme rainfall intensity for durations above three hours is highest in the northern and eastern part of the country (Madsen et al. in prep; WPC 2014). An observable effect of the heat island created by the city of Copenhagen has also been discussed (Madsen et al. 2002, WPC 1999). Figure 3.2 shows the currently applied maps of regional variability for two different design intensities (Gregersen et al. 2014; WPC 2014).

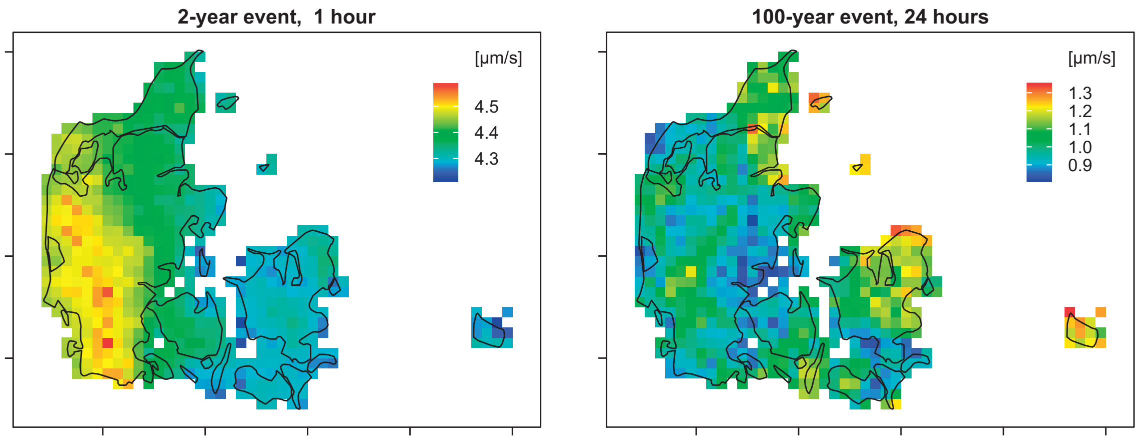

Figure 3.2: Variation of design rainfall over Denmark. Source: Gregersen et al. 2014.

3.3 Teleconnections and large scale drivers

In addition to conditions that create variation in rainfall over space several large scale drivers are known to affect the year-to-year variation. These controlling atmospheric conditions are often divided into opposite phases that each dominates local weather for periods of several years. The most well-known mechanism of the kind is the El Nino Southern Oscillation (ENSO), which has large impacts on temperature and precipitation patterns in the continents on the southern hemisphere (Dai and Wigley 2000; NOAA 2014a). Recent research indicates that the impact of ENSO on extreme precipitation indices goes beyond the countries along the Pacific Ocean; even for Europe a weak influence of ENSO is shown (Kenyon and Hegerl 2010). However, the most important driver of variability in Europe and Scandinavia is the North Atlantic Oscillation (NAO). In the high or positive phase of NAO a strong low pressure system is more often established near Iceland with a corresponding high pressure system close to the Azores, see Figure 3.3. This creates mild but wet weather conditions in Northern Europe and, as a consequence, more heavy rainfall events (Scaife et al. 2008).

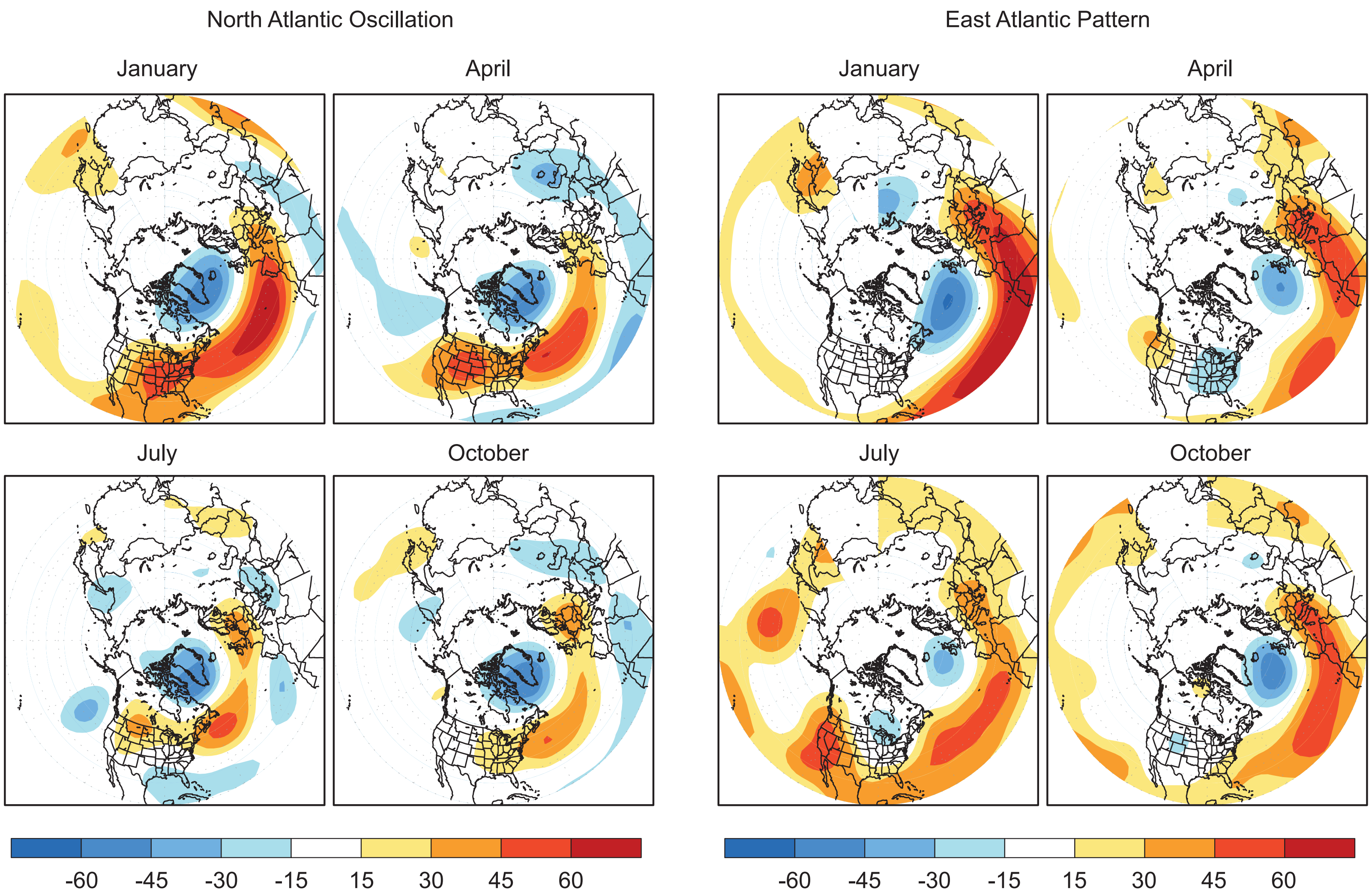

Figure 3.3: Dominant patterns of variability in MSLP over the North Atlantic. The maps show the location of high and low pressure systems when the two teleconnection patterns are in the positive phase. Source: NOAA (2014b), reproduced with permission

Patterns of variation in the mean sea level pressure (MSLP) over the North Atlantic is in the literature derived from Principal Component Analysis (PCA) (Folland et al. 2009; Hurrell et al. 2003; NOAA 2014b), showing that NAO is strongest during winter. Most studies finding a significant correlation between NAO and heavy daily rainfall have hence focused on the winter season (Haylock and Goodess 2004; Kenyon and Hegerl 2010; Lee and Ouarda 2010; Scaife et al. 2008; Willems 2013a). The extreme rainfall events of relevance for urban drainage design occur mainly in the period from late spring to late autumn (e.g. Pedersen et al. 2012). PCA shows that the second most predominant mode of variability in MSLP is the East Atlantic pattern (EA), which in contrast to NAO is in a leading mode the whole year (NOAA 2014b). In comparison to NAO the dipole of low/high pressure systems is located west of England/over Eastern Europe and the Mediterranean in the positive EA phase, see Figure 3.3. Folland et al. (2009) defined a summer NAO (SNAO) that has a slightly different spatial extent compared to the well-defined winter counterpart, with low pressure over Greenland and high pressure over North-western Europe. This pattern is seen from Figure 3.3 (NAO - July) and encompasses also a weak low pressure zone around Gibraltar. A positive SNAO index leads to warm and dry summers in Scandinavia (Folland et al. 2009). Some authors calculate proxies for the NAO/SNAO/EA index from MSLP differences between two stations. In the evaluation of multi-decadal oscillations in extreme rainfall indices over Europe, Willems (2013a) estimated an index from MSLP differences (MSLPD) between a station in Gibraltar, Spain, and two stations in Scandinavia based on data from Jones et al. (1999). The index was found to be highly positively (negatively) correlated to the multi-decadal variations in daily winter rainfall extremes in the Northern (Southern) part of Europe.

In the light of these findings, it is highly relevant to evaluate if the past and present variation of daily rainfall extremes in Denmark are influenced by multi-decadal variations in MSLPD over the North Atlantic. This is assessed using rainfall measurements from 1874 to 2010 (**Paper V**). As in Willems (2013a) a station based index is estimated from MSLPD between a station in Gibraltar and a station in Haparanda, Sweden (the Gib-Hap index). Figure 3.4 shows the annual and multi-decadal variation of this index, in the season where Danish rainfall extremes occur. There is a tendency of an oscillation, even though the pattern is not strictly periodic. Multi-decadal variations in the number of extreme rainfall events are found to covariate with the Gib-Hap index, see Section 5.2 and **Paper V**. Focusing on the more current period (starting in 1979), impact of NAO and EA on daily and sub-hourly rainfall is also evaluated. As expected the variability of EA changes little with the season, see Figure 3.4. The index has been in an ascending phase during the last three decades, and a correlation between the annual number of extreme events and EA is found (**Paper III**). The NAO variability changes with the season, see Figure 3.4. A significant influence of NAO or SNAO is not found (**Paper III)** but Figure 3.4 shows that SNAO exhibits an oscillation pattern, which to some extent resembles the variation in the Gib-Hap MSLPD index. Some similarity between the EA index and the Gib-Hap MSLPD index is also seen from the figure (**Paper V**). EA continues to increase in the last part of period where information on the Gib-Hap MSLPD index not is available.

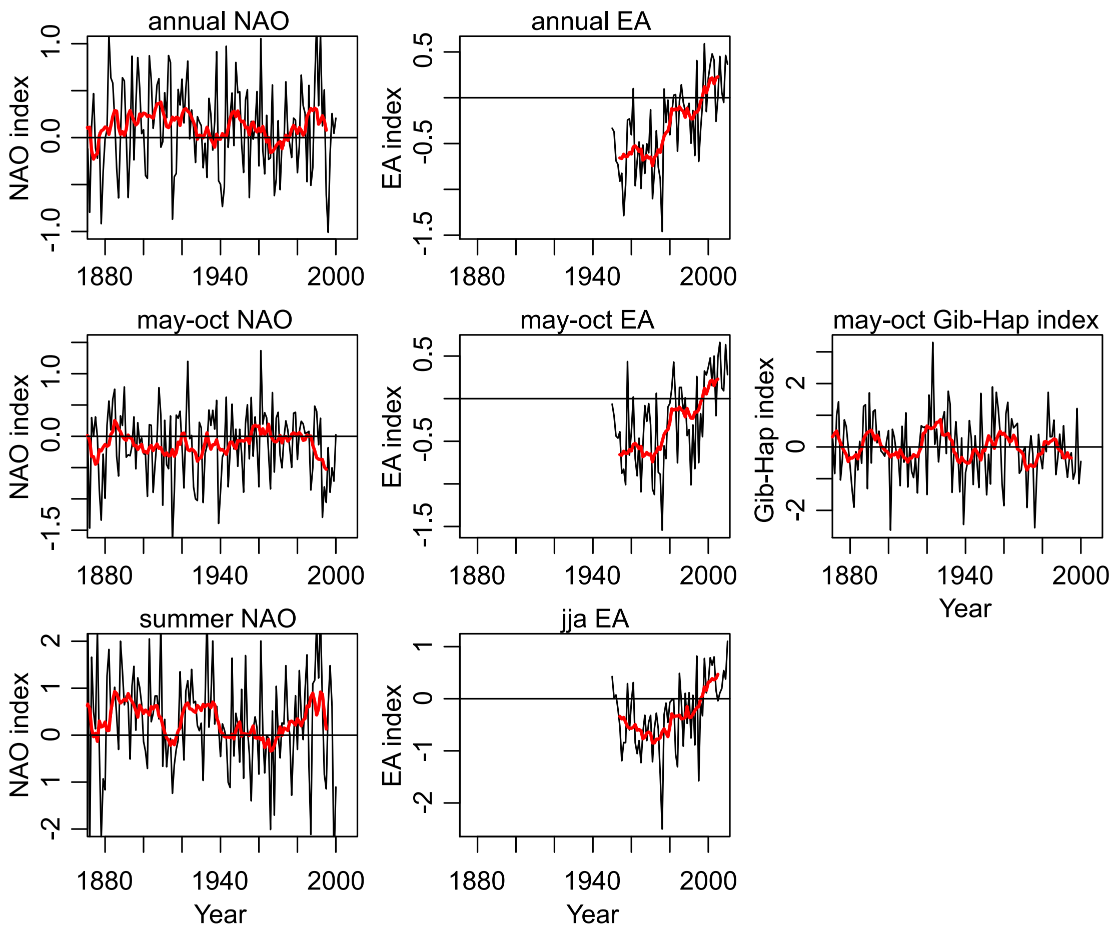

Figure 3.4: Different teleconnections derived from MSLP difference over the North Atlantic

In the search for drivers behind the temporal variation of rainfall extremes in Denmark MSLPD are not the only possibility. The findings discussed above are related to the frequency of extreme events, but while specific atmospheric circulation patterns seem to favour the occurrence of an extreme event, other conditions could affect the intensity, see Section 3.1. Atmospheric rivers were introduced by Lavers and Villarini (2013) as regions of intense moisture transport created by moving cold fronts. The authors showed a link between the formation of strong atmospheric rivers over the North Atlantic Ocean and daily precipitation extremes in Europe. For Denmark the link is weak in the summer due to the lee effect from the Norwegian mountains (Lavers and Villarini 2013). Focusing on the temperature of the ocean Dai (2013) and Enfield et al. (2001) linked multi-decadal variations in the precipitation over US to an oscillation pattern in the Sea Surface Temperatures (SST) of the Pacific and North Atlantic Ocean, respectively. The climate of Denmark is affected by the proximity of the North Sea and the Baltic Sea, therefore analyses of patterns in the SST of the Danish Waters is relevant. A general SST increase, which has intensified during the last three decades, is found. The SST variation is, however, not correlated to the multi-decadal variations of the intensity of the daily rainfall extremes (**Paper V)**. The intensity of the sub-daily rainfall extremes has increased since 1979 but potential driver behind this increase has not been assessed (**Paper II** and **VI**).

3.4 Extreme rainfall under climate change conditions

As mentioned in the introduction, there is strong theoretical evidence that the frequency and/or intensity of extreme rainfall events will increase with the mean global temperature (Fowler and Hennessy 1995; Lenderink and Meijgaard 2008; Trenberth et al. 2003; Westra et al. 2014). Climate change has a longer perspective than the natural variability induced by large scale meteorological drivers and also a permanent impact. Hence WPC recommends that the design intensities are adjusted to reflect the uncertainty related to anthropogenic climate change (WPC 2005; 2008). An evaluation of the impact of mean global temperature changes on the Danish design intensities is therefore highly relevant in the perspective of temporal variability.

Changes in extreme rainfall are expected because at higher temperatures the air can hold more water. The physics behind is contained in the Clausius-Clapeyron equation, predicting the saturation vapour pressure to increase by app. 7% per ^{o}C (Trenberth et al. 2003; Westra et al. 2014). It is explored by several authors if a scaling similar to the Clausius-Clapeyron relation can be found for observed rainfall extremes and for climate model simulations. In relation to sub-daily rainfall extremes generated by convection, it is found that the observed scaling often exceeds 7% per ^{o}C (Berg et al. 2013; Lenderink and Meijgaard 2008).

An increase of the moisture holding capacity is not the only driver for increased extreme rainfall under climatic changes. Changes in atmospheric circulation that favour specific uplift conditions or conditions which enhance the supply of new moist air to storm cells may also play a role, see Sections 3.1 and 3.3. Such changes depend more specifically on the region of interest (Trenberth et al. 2003) and are due to the complicated feedback mechanisms of the climate system best evaluated using climate models.

The resolution of the most common regional climate models is 25x25km^2, hence far too coarse to resolve the convective clouds, see Section 3.1. Instead the models have a convective parameterization scheme, which generates precipitation, but mostly serves the purpose of removing instabilities in the atmosphere that otherwise would lead to model failure (Westra et al. 2014). It is therefore of high relevance to evaluate the output from climate models in relation to realistic simulation of sub-daily rainfall extremes, before using the results for the evaluation of future changes in urban design rainfall. Along with the findings of Hanel and Buishand (2010), Lenderink and Meijgaard (2008), Mayer et al. (accepted) and Sørup et al. (submitted) this PhD study has contributed within this area by suggesting and applying two performance measures for RCM simulation of sub-daily extreme rainfall events. These are

1) Evaluation of the seasonal distribution
2) Evaluation of the spatial structure

In relation to measure no. 1 it is shown that too many of the extreme events in the RCM simulations occur during winter and spring, however with one model preforming better than the other (**Paper II**). In relation to measure no. 2 none of the models simulated a spatial correlation structure for extreme rainfall that is in accordance with the knowledge on the type of rainfall generating the extremes, see Section 3.1 (**Paper II**). Better results are obtained by Mayer et al. (accepted) for RCMs with higher spatial resolution.

Figure 3.5 shows that for the SVK network the correlation range between extreme rainfall events increases with the duration, while it remains constant for both RCMs. From the perspective of urban drainage design and the present need of knowledge on the future design intensities, these findings are very problematic.

A way forward is either:

1) To apply different statistical downscaling methods on the climate model simulations, or
2) To apply climate models with a spatial resolution fine enough to simulate convection without the need for a convection parameterization scheme.

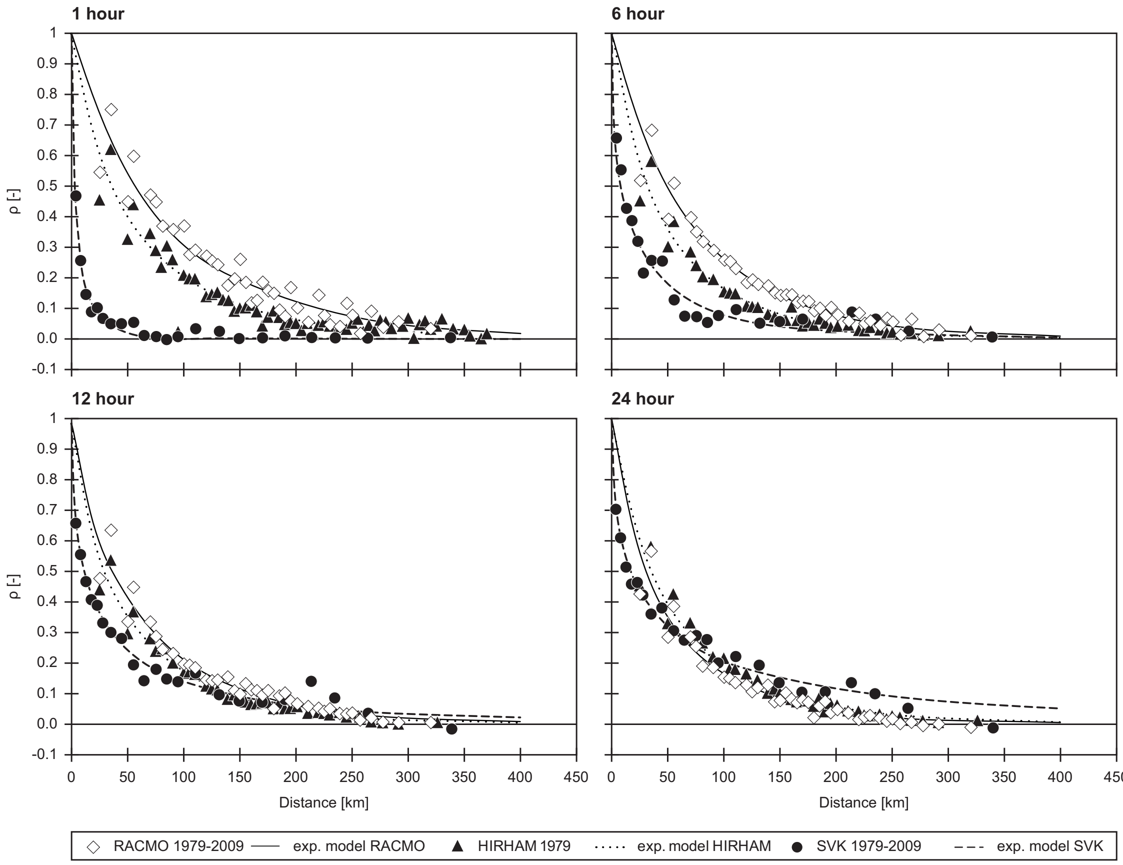

Figure 3.5: The spatial correlation structure for mean intensities of extreme rainfall events with durations of 1, 6, 12 and 24 hours. For the observed rainfall (SVK) the correlation distance increases with the duration as the type of rainfall mechanism changes from convective to frontal. For the simulated rainfall the correlation distance only changes marginally (RACMO-ECHAM and HIRHAM-ECHAM). Details on the estimation procedure are given in Section 4.2.1. Source**: Paper II**.

An extensive review of the many different methods for statistical downscaling is given by Willems et al. (2012), while initial experiments with a convection-permitting RCM having a resolution of 1.5x1.5 km^2 also have been very encouraging (Kendon et al. 2014). However, there is still a long way before an ensemble of transient simulations with this type of model is available. Statistical downscaling is therefore presently the most feasible option. Downscaled climate model simulations are applied to evaluate the possible future change in design intensities expressed as a climate factor (**Paper IV**). Climate factors are presented and discussed in Section 5.4.

4 Statistical modelling of variations in extreme rainfall

Statistical models are required to evaluate the significance of regional and temporal variability of extreme rainfall, and to model the relation to physical covariates. The models are furthermore applied in the construction of Intensity-Duration-Frequency (IDF) curves used by urban engineers. In contrast to Madsen et al. (2002, 2009, in prep.), which only focus on regional variation, one of the major objectives is to develop and apply models that take into account variability in the regional and temporal domain simultaneously. This section briefly introduces the applied statistical theory, the currently applied model and the suggested extension of Madsen et al. (2002, 2009, in prep.).

4.1 Extreme value theory

The extreme value analysis follows the theory of Partial Duration Series (PDS) (Rosbjerg et al. 1992). The annual number of extreme events (N) is assumed to follow a Poisson distribution (**Paper III**):

$$P\left(N_{i,s}=n\right)=\frac{\lambda_{i,s}^{n}}{n!}e^{-\lambda_{i,s}} \quad , \qquad N_{i,s}=0,1,2\ldots \tag{4.1}$$

λ is the rate parameter of the Poisson distribution, corresponding to the average annual number of extreme events. The magnitude of the extreme events is assumed to follow a Generalized Pareto distribution (GPD)

$$F(z)=1-\left(1-\kappa\frac{z-z_0}{\mu(1+\kappa)}\right)^{1/\kappa} \quad \kappa=\frac{1}{L_{cv}}-2,\text{ for }\kappa\neq 0 \tag{4.2}$$

The parameters in the equation are denoted: the location parameter (z_0), the shape (κ) parameter, the mean of the extreme exceedances (μ), and the L-moment coefficient of variation (L_{cv}).

Using this framework a T-year event (z_T) is estimated by:

$$z_T=z_0+\mu\frac{1+\kappa}{\kappa}\left[1-\left(\frac{1}{\lambda T}\right)^{\kappa}\right] \tag{4.3}$$

When sampling the extreme events from a time series, the PDS approach offers two censoring methods. In type 1 censoring, the threshold over which an event is considered as extreme is pre-fixed. The method is also known as Peak over Threshold (POT) (Coles 2001) and the threshold is equivalent to z_0 of the GPD. In type 2 censoring λ is fixed, and thereby also the total number of extremes during the observation period. The optimal choice of censoring methods depends on the data and the nature of the analysis. Both methods have been applied.

In the PDS extreme events are required to be independent (Coles 2001). In the literature there are at least two common ways of ensuring this. Madsen et al. (2002) performed an event-based separation, where each extreme belongs to a specific rainfall event defined by a start and end time. For the events to be independent the dry weather period between two rainfall events must be longer than or equal to the rainfall duration.

4.2 Variations in space

The concept of regional extreme value analysis was established in the 1980s and the most well-known approach is the index-flood method (Hosking et al. 1985; Hosking and Wallis 1993). The motivation was to provide more robust information about design floods by using all available flow or rainfall series within a region, instead of just one single local series. The main idea is to estimate the parameters in the extreme value distribution on the basis of all sites, but allow for a site-specific scaling of one or more parameters in the model.

As a refinement, a regression based approach was developed for PDS (Madsen and Rosbjerg 1997), where regional variations in the parameters of the extreme value distribution are estimated by the theory of L-moments (Hosking 1990) and correlated to geographical or physical characteristics of the region. Examples are MAP or geographical coordinates (longitude/latitude), see Section 3.2. Madsen et al. (2002) applied this approach to estimate urban design intensities for ungauged locations in Denmark, see Figure 3.2. When the regression relationships are established, it is crucial to take into account the effect of correlations between the series of measurements. Two rain gauges close to each other will capture some of the same extreme rainfall events and the series of observations are hence not independent. Another important point is the possible variation of observation period at different sites. This affects the sampling uncertainty, σ_ε, of the individual at-site parameter estimates.

Both components are accounted for using Generalized Least Squares (GLS) (Madsen and Rosbjerg 1997; Stedinger and Tasker 1985) regression.

Introducing the following relationship between the modelled regional extreme value statistic ($\boldsymbol{y}_s$) and the matrix of explanatory variables ($\boldsymbol{X}$)

$$\boldsymbol{y}_s = \boldsymbol{\beta X} + \boldsymbol{\varepsilon}_{\boldsymbol{\Sigma}} \qquad (4.4)$$

where $\boldsymbol{\beta}$ is the regression coefficients and $\boldsymbol{\Sigma}$ the covariance matrix, which in a network with K stations is as follows:

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_{\varepsilon 1}^2 + \sigma_\delta^2 & \sigma_{\varepsilon 1}\sigma_{\varepsilon 2}\rho_{12} & \cdots & & \sigma_{\varepsilon 1}\sigma_{\varepsilon K}\rho_{1K} \\ \sigma_{\varepsilon 2}\sigma_{\varepsilon 1}\rho_{21} & \sigma_{\varepsilon 2}^2 + \sigma_\delta^2 & & & \sigma_{\varepsilon 2}\sigma_{\varepsilon K}\rho_{2K} \\ \vdots & & \ddots & \sigma_{\varepsilon k}\sigma_{\varepsilon s}\rho_{ks} & \vdots \\ & & \sigma_{\varepsilon s}\sigma_{\varepsilon k}\rho_{sk} & & \\ \sigma_{\varepsilon K}\sigma_{\varepsilon 1}\rho_{K1} & \sigma_{\varepsilon K}\sigma_{\varepsilon 2}\rho_{K2} & \cdots & & \sigma_{\varepsilon K}^2 + \sigma_\delta^2 \end{bmatrix} \qquad (4.5)$$

where σ_δ represents the uncertainty of the regression model and ρ the spatial correlation (see Section 4.2.1). σ_δ is assumed to be unknown and is estimated along with the other variables in the regression model using an iterative scheme (Madsen and Rosbjerg 1997). $\sigma_{\varepsilon s}$ is estimated from a-priori knowledge on the sampling uncertainty and depends on which parameter the GLS regression is applied on. To assess the amount of unexplained variability and evaluate if the introduction of explanatory variables is sensible $\sigma_{\varepsilon s}$ is first compared with the total variability of the data. For further information, see Madsen and Rosbjerg (1997) and **Paper VI**. GLS regression is applied in **Paper III** and **VI** for the estimation of the regional variation of λ, z_0 and μ.

4.2.1 Spatial inter-site correlation structure

A framework that estimates the correlation between extreme rainfall events, which originate from the same meteorological event, has been developed by Mikkelsen et al. (1996) for PDS. It suggests a pairing of events from two sites (A and B) that can be regarded concurrent. This is done on the basis of the start time of the event, t_0, and a lag time, Δt, introduced to compensate for the travelling time of the weather systems. Hence, for the i'th extreme intensity measured at site A, Z_{Ai}, to be concurrent with the j'th extreme at site B, Z_{Bj}, the following should be fulfilled:

$$\{Z_{Ai}, Z_{Bj}\}: [t_{0i} - \Delta t, t_{0i} + \Delta t]_A \cap [t_{0j} - \Delta t, t_{0j} + \Delta t] = \emptyset \qquad (4.6)$$

A suitable Δt must be inferred from meteorological knowledge and depends on the rainfall duration.

For an estimation of the unconditional covariance between the two sites, Mikkelsen et al. (1996) introduced a stochastic variable, U, that takes the value 1 when concurrent events exist and 0 otherwise:

$$Cov\{\mathbf{Z}_A, \mathbf{Z}_B\} = Cov\{E\{\mathbf{Z}_A|U\}, E\{\mathbf{Z}_B|U\}\} + E\{Cov\{\mathbf{Z}_A, \mathbf{Z}_B|U\}\} \tag{4.7}$$

The two terms in the equation are derived on the basis of the probability of U taking either of its two possible values, see Mikkelsen et al. (1996). An estimate of the unconditional covariance is obtained by dividing the estimated covariance in Equation (4.7) with the product of the sampling error standard deviations, estimated from the series of extreme values observed at the two stations.

An estimation of the spatial inter-site correlation structure is suggested as a performance measure for RCMs (see Section 3.4 and Figure 3.5) and is furthermore a fundamental part of the GLS model introduced in the section above.

4.3 Variations in time

Temporal variations in the parameters of the extreme value distribution can be assessed by focusing either on periodic long-term fluctuations (**Paper V**) or specifically on increasing/decreasing trends (**Paper II**, **III** and **VI**). When significant tendencies are identified, a possible correlation with large-scale drivers can be tested, see Section 3.3. The approaches applied in this thesis are reviewed in the sections below.

4.3.1 Periodic fluctuations

Different approaches to evaluate periodic fluctuations exist in the literature. Lee and Ouarda (2010) addressed the occurrence of oscillating patterns in hydrological series by means of Empirical Mode Decomposition in the frequency domain. Here a finite number of sequences are defined, representing the main frequencies of the variations. The significance of the contribution from each frequency is tested. Ntegeka and Willems (2008) applied a moving window of 5-15 years as a filter to enhance the multi-decadal variations only. The filter can be expressed as a perturbation factor (*pf*), where a selected extreme value characteristic ($C_{extreme}$) is calculated for both the subseries (t_{sub}), defined by the moving window, and the full series (t_{full}):

$$pf = \frac{C_{extreme}(t_{sub})}{C_{extreme}(t_{full})} \tag{4.8}$$

This filter generates a series of perturbation factors that are highly autocorrelated and therefore, potentially, exhibit a pseudo-oscillatory behaviour. Therefore, patterns of variability found in the smoothed series needs to be retrieved from the original series as well. This study estimates *pf* values for both the average annual number of events (pf_λ) and the mean extreme intensity (pf_μ). Variations in the frequency domain are evaluated by spectral analysis based on a Fast Fourier Transformation (Shumway and Stoffer 2010) for the series of λ, μ, pf_λ and pf_μ. Regional similarities between the analysed sites are discussed, but no regional test statistics are formulated. For further details see **Paper V**.

4.3.2 Linear regression

In line with the regional GLS model introduced in Section 4.2, a temporal GLS model can be formulated, where the parameters in the extreme value distribution are estimated on an annual basis averaging over all stations. Assuming no correlation between the annual estimates, only the sampling uncertainty must be taken into account in the GLS regression. Introducing the following relationship between the modelled temporal extreme value statistic ($\boldsymbol{y}_i$) and the matrix of explanatory variables ($\boldsymbol{X}$)

$$\boldsymbol{y}_i = \boldsymbol{\beta X} + \boldsymbol{\varepsilon}_{\boldsymbol{\Sigma}} \tag{4.9}$$

where $\boldsymbol{\beta}$ is the regression coefficients and $\boldsymbol{\Sigma}$ the covariance matrix, which in the case of M observation years is as follows:

$$\boldsymbol{\Sigma} = \begin{bmatrix} \sigma_{\varepsilon 1}^2 + \sigma_\delta^2 & 0 & \cdots & \\ 0 & \sigma_{\varepsilon i}^2 + \sigma_\delta^2 & & \\ \vdots & & \ddots & \\ & & & \sigma_{\varepsilon M}^2 + \sigma_\delta^2 \end{bmatrix} \tag{4.10}$$

σ_δ is estimated along with the other variables in the regression model, while $\sigma_{\varepsilon i}$ is estimated from a-priori knowledge on the sampling uncertainty and depends on which parameter the GLS regression is applied on. The variance of the sample mean is affected by the spatial correlation among the stations. If the stations are heavily correlated, the equivalent number of independent stations, K_{eff}, is substantially lower than the actual number of stations in the network, K (**Paper VI**):

$$K_{eff} = K(1 + (N-1)\hat{\rho})^{-1} \tag{4.11}$$

where $\hat{\rho}$ is the average correlation among the stations. For further information on the estimation of $\sigma_{\varepsilon s}$ and the use of K_{eff}, see **Paper VI**. GLS regression is applied in **Paper VI** for the estimation of the temporal variation of $z0$ and μ, while **Paper II** uses ordinary least squares (OLS).

While GLS allows the model residuals to exhibit a certain correlation structure, Generalized Linear Models (GLM) provide another extension to the ordinary linear model, by allowing the model residuals to follow one of the many distributions belonging to the exponential family (Dobson 2002; Faraway 2006) and not only the traditional normal distribution. Parameter estimation is performed by maximum likelihood, and restrictions on the sample space are complied with by use of a link function. Using this approach the temporal variations of λ can be modelled, while taking into account that the underlying data are generated by a Poisson Process, see Section 4.1. A GLM for Poisson data is known as Poisson Regression (PR). This model can also take the observations period into account as an offset and applies the natural logarithm as a link function (Dobson 2002; Faraway 2006). PR was applied in **Paper II** and **III**.

4.4 Spatio-temporal models

A main objective is to derive a spatio-temporal model that can provide an extension to Madsen et al. (2002; 2009) by accounting for variability in the temporal domain.

In the literature Bayesian hierarchical models are often used to describe spatio-temporal variations of extremes (Aryal et al. 2009; Heaton et al. 2011; Sang and Gelfang 2009; Sun et al. 2014). They have the advantages of not relying on strict assumptions on the underlying density function, as Markov Chain Monte Carlo methods are used to quantify parameter uncertainty. There are differences on how the regional variation is described; by geostatistical methods (Aryal et al. 2009), a trivariate Gaussian process (e.g. Cooley 2007; Heaton et al., 2011) or a combination of the latter and regression (e.g. Dyrrdal *et al*. 2014; Ghosh and Mallick 2011; Renard 2011). Some studies disregard the spatial dependence between stations, but those including it apply copula functions (Ghosh and Mallick 2011; Renard, 2011). While this has the advantage that the parameters of the correlation functions are estimated simultaneously with all other model parameters, assumptions regarding the type of copula function are unavoidable and difficult to validate. Despite the recent advances within Bayesian hierarchical extreme values models, there is still no formulation in the literature for a spatio-temporal model based on PDS data from a rain gauge network with a varying number of annually active stations.

Other spatio-temporal extreme value models include the non-stationary index flood approach (Roth et al. 2012) and models based on max-stable theory (Thibaud et al. 2013; Westra and Sisson 2011).

This PhD study suggests an alternative approach, which combines the theory of Section 4.2 and 4.3 into a model that captures regional and temporal variations simultaneously. The model is based on the theory of Generalized Estimation Equations (GEE) (Halekoh et al. 2006; Hardin and Hilbe 2003), which is an extension to the GLM procedure and hence abbreviated GLMGEE. The model takes information about the correlation of the residuals into account when the maximum-likelihood equations are solved.

The GLS model divides the variance into sampling uncertainty and model uncertainty. A similar division is not obtained from the GLMGEE procedures; here the effect of the observation period can either be included as an offset, or determined by a weight for each data point in the regression. The correlation between stations is estimated as a function of the distance (see Section 4.2.1) and included in the GLMGEE equations. In the applied GLMGEE implementation, written by Halekoh et al. (2006) for the statistical language R, correlation matrixes are estimated for each individual year using information on active station (**Paper III**). Table 4.1 gives an overview of the applied GLMGEE models. The assumption on the underlying density function must be validated by residual analysis (Faraway 2006).

Table 4.1: Applied GLMGEE procedures

GPD parameter	Density function	Link function	Observation period	Paper
λ, N	Poisson	log	as offset	III, VI
z_0	Gaussian	identity	as weight	VI
μ	Gamma	log/inverse	as weight	VI

Several studies discuss the necessity of a non-stationary threshold in type 1 censoring/POT analysis (e.g. Kysely et al. 2010; Roth et al. 2012). The non-stationary threshold function is in these studies estimated from quantile regression. This method is not applicable for the data analysed by Madsen et al. (2002, 2009, in prep.) due to the applied method for defining independent events (for details see **Paper VI**). Therefore, this study develops an alternative threshold model based on type 2 censoring. To follow the previous regional models the average rate of extremes must be approximately 3 events/year/station. Therefore, the following procedure is applied:

1) For each year at each station, the recorded extreme with rank four is sampled as a predictor for z_0.
2) A regression model is constructed for z_0, evaluating regional and temporal variations and possible explanatory variables.
3) The final spatio-temporal model for z_0 is applied as the threshold to define a new PDS for each station using type 1 censoring.
4) λ, μ and L_{CV} are computed, and their regional and temporal variation are accessed. For the threshold model to be successful, λ must be constant over space and time.

The model validation and application is discussed in Section 5.3.

5 Variations of design rainfall in Denmark

The recommended design intensities in Denmark have, as mentioned in Section 1.1, been updated four times since the first publication in 1950, partly alongside advances in extreme value modelling and knowledge on rainfall variability. This section presents and discusses the findings of the PhD study of relevance for present and future guidelines on design intensities. The starting point of the discussion is the situation at the initiation of this PhD study.

5.1 Historical guidelines and observed changes in design intensities

In the two first WPC guidelines on design intensities no extreme value modelling is applied (WPC 1950; 1974). Figure 5.1 shows the scattered estimates of a 2-year event with a duration of 10 minutes obtained from the gauges installed in 1933. In WPC (1974) one regional collection of design rainfall was formed by aggregating all series, with the purpose of reducing the uncertainty on the design intensities. However, both regional and temporal correlation was disregarded. The IDF relationship estimated from this series is known as 'Landsregnrækken' WPC (1974), but was later replaced by a regional model based on the SVK rain gauge network (WPC 1999). With this model the recommended design intensities decreased, see Figure 5.1.

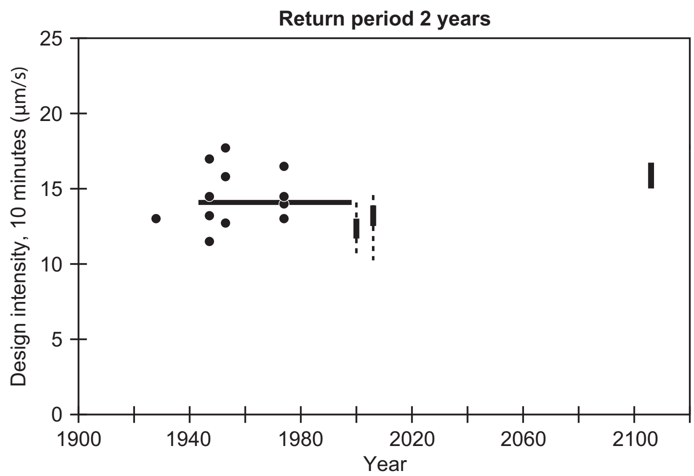

Figure 5.1: Changes in the recommended design values for a return period of 2 years. Points represent local estimates from the gauges installed in 1933, the horizontal line represents Landsregnrækken, vertical lines represent the variation over Denmark in regional models from WPC 1999 and 2006. The final line in 2110 accounts for climatic changes from WPC 2005. Punctured lines show the range between the highest and lowest station-based estimate. Source: Modified from Arnbjerg-Nielsen (2011).

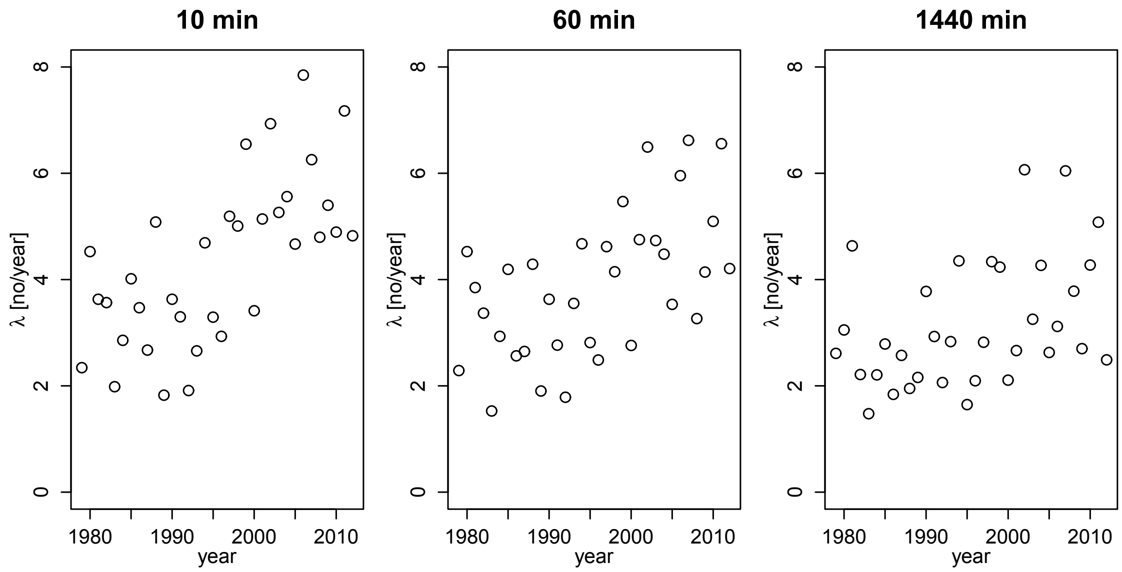

Figure 5.2: Annual development in the number of extreme events (λ) between 1979 and 2012, for 10, 60 and 1440 minutes, calculated as a regional average of all the SVK stations. The underlying PDS has a constant threshold of 6, 2.1 and 0.26 µm/s, respectively. Source: Gregersen et al. (2014) and **Paper II** with an updated period of observation.

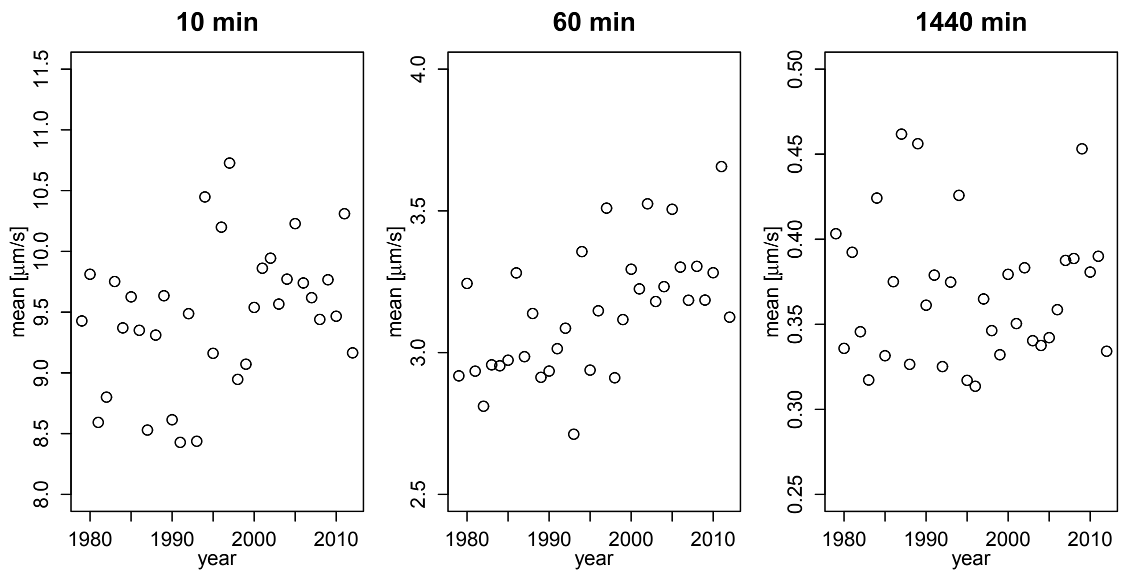

Figure 5.3: Annual development in the mean intensity (μ) of extreme precipitation events between 1979 and 2012, for 10, 60 and 1440 minutes, calculated as a regional average of all the SVK stations. The underlying PDS has a constant threshold of 6, 2.1 and 0.26 µm/s, respectively. Source: Gregersen et al. (2014) and **Paper II** with an updated period of observation.

The decrease in design intensities from WPC (1974) to WPC (1999) was, at that time, regarded as an impact of the change in statistical methodology combined with improved data. However, an update of the regional model in 2005 showed increasing design intensities and gave the first indication of non-stationary extreme rainfall conditions. This is also seen by analysis of the temporal development in λ and μ in Equation (4.3). Both showed indications of increase, see Figure 5.2 and Figure 5.3.

The final component of Figure 5.1 is a projection of future design intensities in a world affected by anthropogenic climate change. In WPC guidelines from 2006 it is recommended to account for increases of 20, 30 and 40% for a 2- , 10- and 100-year event, respectively, for a projection period of 100 years (WPC 2006). The estimations are based on one RCM simulation assessed by three different downscaling procedures. The uncertainty of the estimates is acknowledged and discussed, but no confidence bands are given.

Inspired by the historical changes, reflected in Figure 5.1, it is highly relevant to evaluate long-term variation in the two extreme value statistics. From this, the increase from 1979-2012 can be put into perspective. Furthermore, the possibilities for extending the regional model with a non-stationary component must be considered. Finally, guidelines for including the potential impact of anthropogenic climate change are discussed in the light of the finding of this thesis.

5.2 Long-term variations in extreme rainfall

Following the methodology of Section 4.3.1 long-term variations in λ and μ are estimated using the five long DMI series with daily measurements. For the station in Copenhagen the dominant pattern of variability in λ is on the multi-decadal scale. It has a recurrence period of approximately 40 years, but the cycle lengths are somewhat irregular, see Figure 5.4 and Figure 5.5. It should be noted that the year-to-year variability is high, see Figure 5.5, and that the frequency-analysis indicates several other dominant patterns of variability with shorter recurrence periods, see Figure 5.5. In addition to the periodic fluctuations, λ also exhibits a general increase. When comparing λ at the SVK station in Søborg with the pattern of the long series, it is seen that the two agree well, and that the measuring campaign in Søborg was initiated just at the point of inflection, see Figure 5.5.

Analyses of all five series are given in **Paper V**. Here it is shown that λ exhibits a general increase from 1874-2010. The periodograms for the other stations also show a peak representing variations with a frequency of 25-40 years, but apart from a regional low in the late 1980s, periods with a high/low average number of extremes are not aligned. Data from other DMI stations (see Section 2.1) confirm a countrywide low in the late 1980s. They also show a better agreement in the pattern of variation, for stations in the eastern part of Denmark (**Paper V**)

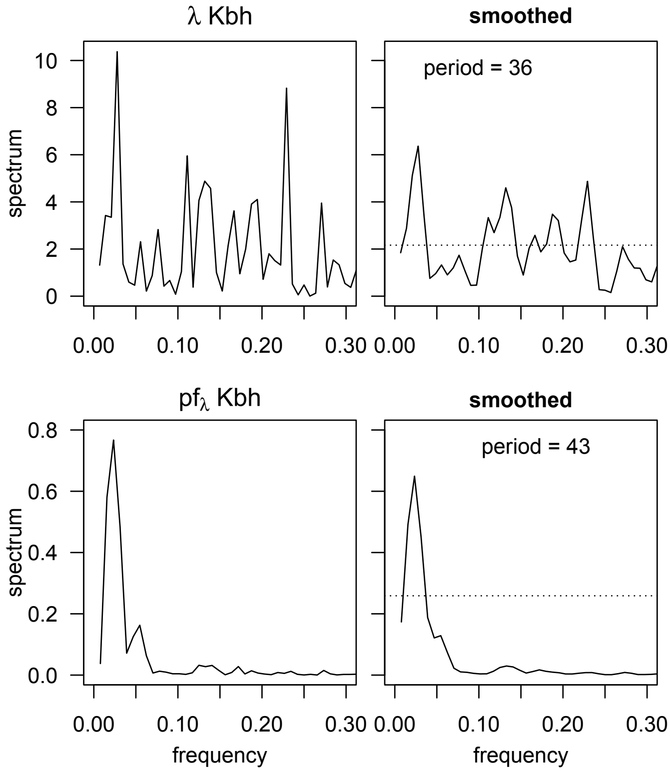

Figure 5.4: Periodograms from a spectral analysis based on FFT of the annual number of extreme events at the DMI station in Copenhagen. The graphs on the right are smoothed periodograms where the horizontal line represents the lower 95% confidence interval of the maximum peak (Shumway and Stoffer 2010). The lower set of graphs is for the smoothed series where Equation (4.8) has been applied with a window length of 10 years. This enhances the low frequency variability significantly. Source: Modified from **Paper V**.

The regional increase of λ, see Figure 5.2, is correlated to the increase of the EA summer pattern (see Section 3.3 and **Paper III)**. A correlation is also found between the multi-decadal variation of pf_λ for Copenhagen and the MSLPD between Haparanda and Gibraltar in **Paper V**, see Figure 3.4. The Gib-Hap MSLPD index has a point of inflection in the 1980s and so has the EA index. It is difficult to explain the difference in the pattern of multi-decadal variability over Denmark (**Paper V)**. The climatic differences over

Denmark (see Section 3.2) are currently not understood well enough to provide a clear explanation.

Analysis of long-term variability of μ shows no general increase and no apparent multi-decadal fluctuations (**Paper V**). A weak correlation between pf_μ for the station at Samsø and the SST of the Danish waters is found. However, as seen by Figure 5.3, the increase in the short duration extremes is not found at the daily level. This could indicate that the change is driven by changes in the convective precipitation mechanisms. The long daily DMI series cannot be used to asses this.

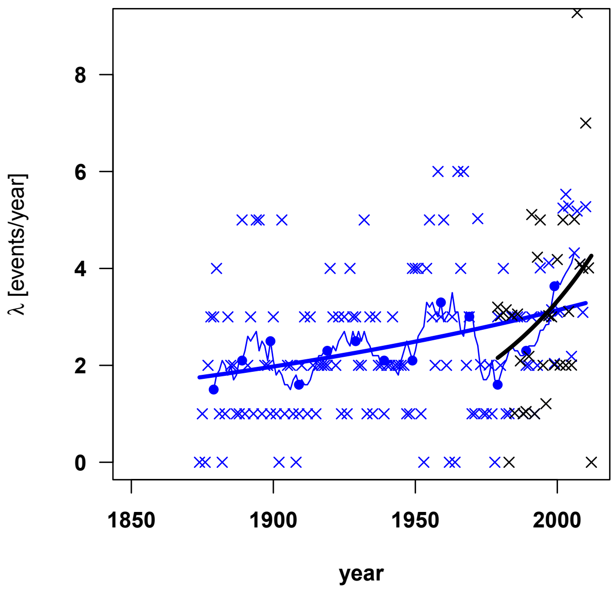

Figure 5.5: Annual development in λ between 1874 and 2012 for the daily accumulated rainfall depth, estimated from the long DMI series from Copenhagen (blue) and the SVK station in Søborg (black). Crosses are the annual number of extreme events, filled circles are the 13 independent points generated by a block average of 10 years, thin lines are the smoothed series and thick lines the modelled increase. Source: Gregsersen et al. (2013).

Returning to the variations of design intensities discussed in Section 5.1, Equation (4.3) shows that variations in z_T mainly are controlled by variations in λ for small values of T. Analysis of a long rainfall series from Belgium with a resolution of 10 minutes indicates that the multi-decadal variability in 10 minutes rainfall extremes also are reflected in daily rainfall extremes (Gregersen et al. 2014). From this, it is concluded that there, in part, are natural drivers behind the variation in λ and therefore behind the variations in the design intensities for urban drainage for small values of T. This conclusion does not rule out a possible influence of anthropogenic climate change, i.e. driving the general increase over the entire observation period. For further discussion on the interaction between anthropogenic climate change and large scale drivers, see Section 5.4. The driver behind the increase in μ for short duration rainfall is still unknown.

5.3 A non-stationary and regional model for the present

The regional increases in λ and μ are evaluated by the methods from Section 4.3.2 (**Paper II, III, VI** and Gregersen et al. 2014**).** This shows an increase in both parameters over the observation period, depending on the rainfall duration and the applied regression procedure, see Table 5.1. It is seen that the significance of the increase depends on the inclusion of information on correlation between the stations, see Eq. (4.11) Section 4.3.2.

Table 5.1: Estimates of the increase in the PDS parameters, standard deviation is given in parenthesis.

PDS parameter		10 min	60 min	180 min	1440 min
λ	slope	2.39	2.28	1.80	1.73
Poisson regression	[%/year]	(0.41)	(0.49)	(0.64)	(0.68)
	p-value	<0.01	<0.01	<0.01	0.01
λ	slope	0.10	0.076	0.053	0.047
Marginal GLS	[event/year^2]	(0.028)	(0.027)	(0.026)	(0.028)
	p-value	<0.01	0.01	0.05	0.1
μ	slope	0.018	0.012	$4.97 \cdot 10^{-3}$	$3.17 \cdot 10^{-5}$
Marginal OLS	[µm/s/year]	($9.11 \cdot 10^{-3}$)	($3.24 \cdot 10^{-3}$)	($1.73 \cdot 10^{-3}$)	($6.17 \cdot 10^{-4}$)
	p-value	0.06	<0.01	<0.01	0.96
μ	slope	0.019	0.013	$5.90 \cdot 10^{-3}$	$1.15 \cdot 10^{-4}$
Marginal GLS	[µm/s/year]	($9.51 \cdot 10^{-3}$)	($3.59 \cdot 10^{-3}$)	($1.83 \cdot 10^{-3}$)	($5.99 \cdot 10^{-4}$)
	p-value	<0.01	<0.01	<0.01	0.84

Because the Poisson regression procedure includes a logarithmic link function the estimated slope is given as a percentagewise increase per year.

The increase in λ is significant and therefore problematic for the assumptions of stationarity imbedded in the regional model, see Section 4.2. The results show that this assumption is not fulfilled for the SVK data. Therefore, the regional model is dominated by extreme events that occur in the end of the observation period. The problem is enhanced because the SVK network has many more active stations in the end of the observation period (Madsen et al. in prep). This results both in a higher sampling uncertainty and higher uncertainty on the estimated regression parameters.

The purpose of the spatio-temporal GLMGEE model presented in Section 4.4 is to account for temporal variability. The model is found qualified for adjusting the invalid assumption of stationary conditions (**Paper VI**). An important feature of the model is the non-stationary regional threshold that ensures a constant λ.

The following relationship is suggested for estimation of design intensities with a return period of T years (**Paper VI**):

$$z_{T,i,s} = z_{0,i,s} + \mu_{i,s}\frac{1+\kappa}{\kappa}\left[1-\left(\frac{1}{\lambda T}\right)^{\kappa}\right] \tag{5.1}$$

The threshold (z_0) is pre-fixed but varies over time and space, the average number of extreme events (λ) is constant and slightly above 3 event/year in correspondence with the value applied by Madsen et al. (in prep.). The mean of the extreme exceedances (μ) varies also over time and space for some durations. The shape parameter (κ) can be assumed homogeneous over the entire region, due to the large sampling uncertainty on this parameter. Parameter estimates are given for rainfall durations of 10, 60, 180 and 1440 minutes in **Paper VI** and summarized in Table 5.2 for two of the four durations. In the PDS censored with a spatio-temporal threshold, the change in μ over time differs slightly from Figure 5.3; for some durations the marginal GLS model shows a significant increase over time.

These are furthermore used for the estimation of design intensities for a return period of two years and a rainfall duration of 10 minutes, see Table 5.3. The 2-year events estimated from Eq. (5.1) show good agreement with the estimates from the three WPC publications on design rainfall estimated from the SVK network. Due to the increased number of active stations in the last decade, the WPC (2014) model gives higher predictions than Eq. (5.1) applied for the median of the observation period (i = 1996). Instead the two models give similar estimates at year 1999. The apparent lack of variability with MAP is due to rounding.

Table 5.2: Parameters for estimation of the design intensities that varies in time and space.

$z_{0,i,s}$			
10 min	$z_{0i,s} = 4.04 + 0.0018 \cdot MAP + 0.081 \cdot time$		
1440 min	$z_{0i,s} = 0.067 + 2.4 \cdot 10^{-4} \cdot MAP + 0.0013 \cdot time$		
λ			
10 min	$\eta = -4.65$	where	$\eta = \log(\lambda)$
1440 min	$\eta = -4.73$	where	$\eta = \log(\lambda)$
$\mu_{i,s}$			
10 min	$\eta_i = 0.33 - 2.6 \cdot 10^{-3} \cdot time$	where	$\eta_i = (\mu_i)^{-1}$
1440 min	$\eta_s = 47.97 - 1.42 \cdot \mu_{CGDs}$	where	$\eta_s = (\mu_s)^{-1}$
κ			
10 min	$\kappa = -0.13$		
1440 min	$\kappa = -0.15$		

The assumptions behind the GLMGEE models used for each parameter are given in Table 4.1, some of them imply the use of a link function. The temporal variable *time* is the number of years since 1978, while the two regional variables, *MAP* and μ_{CGD}, are the Mean Annual Precipitation and the mean daily extreme rainfall estimated from a regional climate grid that covers Denmark, respectively. For further information see **Paper VI**.

Table 5.3: Regional estimates of a 2-year event with a duration of 10 minutes for four Danish cities.

2 year event [μm/s]		**Gentofte/ Søborg**	**Aarhus**	**Odense**	**Aalborg**
WPC (1974) pooled series	1933-1962	13.7	13.7	13.7	13.7
WPC (1999) regional model	1979-1996	12.2	12.3	12.2	12.3
WPC (2006) regional model	1979-2005	13.0	13.1	13.0	13.1
WPC (2014) regional model	1979-2012	13.9	14	13.9	14.0
Eq. (5.1) and **Paper VI**	i = 1996	13.5	13.5	13.5	13.5
Eq. (5.1) and **Paper VI**	i = 2005	14.8	14.9	14.8	14.9

Gentofte/Søborg represents Copenhagen. The assumptions behind the applied regionalisation in the four WPC reflect the state-of-art at the time of publication.

It is important to emphasise that Eq. (5.1) cannot be used for prediction beyond 2014, as physical drivers for the temporal development are not included. As discussed in Section 3.3, the driver behind the temporal change in the frequency and thereby the temporal change of z_0 is most likely MSLP differences over the North Atlantic, while the driver behind the temporal change in μ could be SST. The model can be modified to include both, when their present and future influence is confirmed.

The spatio-temporal GLMGEE model can also be used to compare the magnitude of variability in the regional and temporal domain (**Paper III**). Looking at the number of extreme rainfall events (*N*), for a rainfall duration of 24 hours, the applied regional explanatory variables reduces the variability by 2.8 %. In comparison, the applied temporal explanatory variables reduce the variability by 18 % (**Paper III**).

5.4 Design intensities for the future

The number of available climate model simulations for Denmark has increased remarkably since the WPC recommendations from 2006. The data from the ENSEMBLES database (see Section 2.2) are presently the best basis for evaluation of future change. With an ensemble of climate models and a selection of well-established downscaling methods it is possible to estimate a confidence band for the expected change in the design intensities. As a part of the PhD study the results of the following downscaling methods have been assessed (**Paper IV)**: A delta change approach for extreme events (Larsen et al. 2009), a weather generator (Burton et al. 2008) combined with disaggregation (Molnar and Burlando 2005) and a method using climate analogues (e.g. Hallegatte et al. 2007). The expected change in the design intensities is often communicated as a climate factor (CF), representing the ratio between the future design intensity and the present design intensity. Figure 5.6 shows the range of estimated CFs for hourly design intensities. It is important to emphasise the danger of underestimating the width of the confidence bands, both because the climate models in the ensembles are not independent (Sunyer et al. 2013; Sunyer et al. 2014) and because the ENSEMBLES database only represents one emission scenario, see Section 2.2.

The three different downscaling methods give similar results and all of them point towards an increase of the design intensities in the future. In relation to the climate models ability to simulate sub-daily rainfall extremes (see Section 3.4 and **Paper II**), neither the Weather Generator nor the Climate Analogue relies on sub-daily rainfall extremes from the climate model. Sørup et al. (in prep) have analysed a more advanced version of the applied weather generator. They found that the mean intensities of the simulated extreme rainfall events have a spatial correlation structure similar to observed rainfall (see Figure 3.5).

The A1B scenario, which forces all ENSMBLES simulations, represents less intense greenhouse gas emissions over a 100 year projection horizon, compared to other IPCC scenarios (IPCC 2000; van Vuuren et al. 2011). Gregersen et al. (2014) therefore included single simulations with high emission scenario forcing, to evaluate the effect of the scenario on the projected change in design intensities, see Figure 5.6. Based on a subjective assessment of all the available knowledge discussed above, WPC (2014) and Gregersen et al. (2014) recommend standard CFs of 1.2, 1.3 and 1.4 for 2-, 10- and 100-year return periods, respectively, and high CFs of 1.45, 1.7 and 2.0. The standard CFs are to be used in design of urban drainage systems, ensuring that the systems build today also comply with the service levels in the future. The high CFs are recommended for use in worst-case simulations to test the robustness of the system.

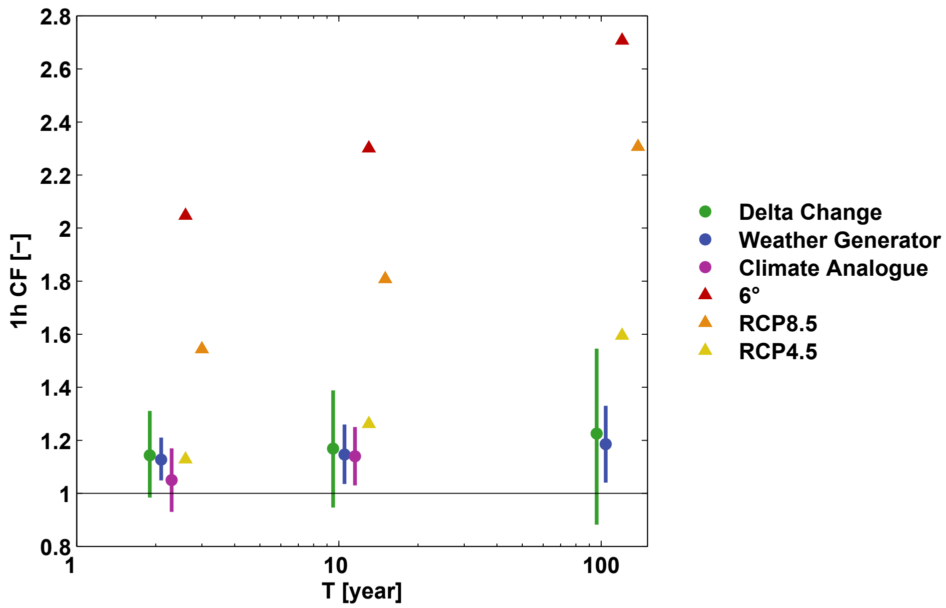

Figure 5.6: Climate factors (CF) for 1 hour precipitation extremes for different return periods (T). The results from the three downscaling methods applied on the ENSEMBLES data are given in green, blue and magenta, where the vertical lines represent 68% confidence limits with the centre as the most probable value. The Climate Analogue did not achieve a result for z_{100}. The triangles show the results of single simulations forced by three alternative emission scenarios. All CFs are for a 100 year projection horizon. Source: Modified from **Paper IV** and Gregersen et al. (2014).

5.5 Handling the uncertainty of the urban design intensities

With the findings from WPC (2014) and Gregersen et al. (2014) Figure 5.1 can be updated, see Figure 5.7. The new regional model is added to the figure together with the recommendations on design rainfall in the future estimated from the standard CF and the high CF. In comparison to Figure 5.1 the new figure also shows how the recommendations on future design rainfall have changed. The non-stationary and regional model is not yet implemented in any WPC recommendations, but it is indirectly reflected by Figure 5.7 as the change in design rainfall from 1999 to 2014. An extrapolation of the trend observed from 1979 to 2012 gives a value 2114, which is higher than the value obtained when the high CF is applied. This illustrates the importance of natural variability, even though extrapolation is strongly dissuadable. From the new knowledge on possible natural fluctuations of the rainfall extremes in the past we concluded, that the increase in the number of rainfall events is not likely to continue at the same rate in the following decades, see Section 5.2.

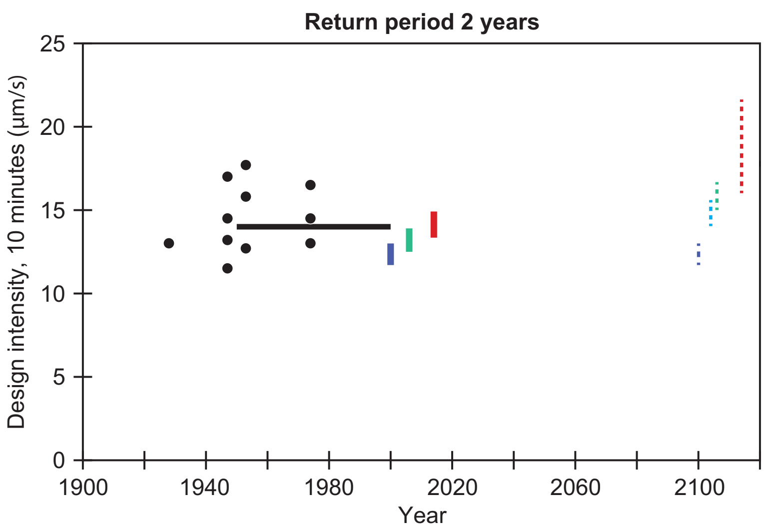

Figure 5.7: Updated version of Figure 5.1 including the findings of WPC (2014) and Gregersen et al. (2014), which is the most recent regional model given by the vertical bold red line (year 2014) and the updated climate factors given by the punctured red line (year 2114). Points represent local estimates, the horizontal line represents Landsregnrækken, vertical blue lines represents the variation over Denmark in WPC (1999), vertical turquoise lines represents WPC (2005) and vertical green lines represents WPC (2006). All punctured lines are projections of future intensities made 100 years earlier.

The IPCC states that for many decades to come it is not possible to separate the influence of anthropogenic climate change from the influence of natural variability, but they do not address the effect of a possible interaction (IPCC 2013). Based on the findings in Section 3.3, a hypothesis is that the variation in the frequency of extreme events is mainly driven by teleconnections. Climate change can, and likely will, alter the atmospheric circulations patterns. Probably, the overall global temperature change determines how critical this change will be. Whether interaction already plays a role and is partly responsible for the increase over the last 34 years cannot be concluded from the analyses presented here.

The importance of natural fluctuations is evaluated by assessing if the pattern described in Section 5.2 has affected design practices in the past. In the late 1980s and early 1990s the low number of urban floods was ascribed to technological and scientific advances, while legislative initiatives focused mainly on water quality. In Section 5.2 this period is shown to have relatively few extreme rainfall events due to natural variability. This example, in part, illustrates what influence of natural variability we can expect in the future.

In the context of urban drainage design, it is possible to take the uncertainty of natural variability into account, also if the drivers and future projections of these are unknown. Willems (2013b) discussed possibilities for adjustment of extreme rainfall statistics accounting for multi-decadal fluctuations. Arnbjerg-Nielsen (2011) presented a framework for managing inherent uncertainties in design of drainage systems. The framework includes, among others, the uncertainty related to the projected change in paved areas connected to the drainage system and the uncertainty of the anthropogenic climate change. The change in design intensity estimated from periods of relatively few and relatively many extremes, respectively, can also be included in this framework.

With WPC (2014) and Gregersen et al. (2014) the first attempt is made to evaluate and communicate the magnitude of uncertainty for the climate factor. This is done by estimation of a high factor that represents the upper 84% confidence level and a recommendation on when to apply it. However, it is recognized that the uncertainty of the climate factors is, and will remain, underestimated. No matter how many scenarios, climate models and downscaling methods we apply, the uncertainty prevails. There are features in the climate systems that we do not understand and cannot model, but most important is the irrational behaviour of mankind. In relation to emission scenarios, but also in terms of the requirements to cities of the future, which we presently design our sewer systems for (**Paper I**). Recognising this uncertainty and its persistent nature is an important first step. Several frameworks exist, which can be used to evaluate different adaptation strategies (e.g. Clarke. 2008; Harremoes et al. 2002) among others the precautionary principle, the minimax strategy and Bayesian decision strategy (**Paper I**). To illustrate the use for decision making in relation to climate change adaptation in urban drainage design these frameworks are applied for simple constructed examples. The case study used to illustrate Bayesian decision strategy applies an example with a creek, which floods a residential area. Houses are built assuming that the creek exceeds the banks on average once in 50 years. The perceived flood risk change substantially after one flood, but Bayes' Theorem (**Paper I**) can estimate the statistical probability of the true rate of flooding being higher than originally assumed. This probability increases (decreases) after years with floods (no floods), and it provides a measure on which decisions can be made; if the probability reaches a critical level the banks of the creek must be enforced. For more details see **Paper I**. More advanced examples using Bayesian networks for decision support is given by e.g. Åström et al. (2014).

The minimax strategy has evolved from game theory and is applied to explore the action of two opposite actors, whose benefits and costs depend on the action of the other. However, the first player does not know the move of the other, and will therefore act to minimise his own potential cost. The minimax strategy can be applied for a situation where the two actors are; the future state of the world and a political adaptation strategy, respectively. In relation to adaptation of urban drainage system a CF ($CF_{applied}$) must be selected, but the true CF (CF_{true}) of the future remains unknown. There is a potential danger of implementing a very ambiguous and expensive adaptation strategy, while the expected impacts of climate change fail to happen. **Paper I** applies the minimax strategy with the nine combinations of $CF_{applied}$ and CF_{true} values of 1, 1.4 and 2. It is shown that if the adaptation is based on a CF that turns out to be overestimated, it will still reduce the extent of flooding. The optimal minimax strategy for the analysed case study is a CF of 2. These findings indicate that the uncertainty of the future (whether dominated by natural fluctuations, anthropogenic climatic changes or both) should not be a hindrance for initiation of adaptation.

6 Conclusions

The thesis has found potential drivers of extreme rainfall variation, based on a literature review and explorative data analysis, with focus on daily and sub-daily rainfall durations. The explorative data analysis concludes that the number of extreme rainfall events, smoothed by a 10-year moving average, has fluctuated between periods of relative high and periods of relatively low number of events over the last 137 years. The significant increase observed over the last 34 years fits well into this pattern. MSLP differences over the North Atlantic show a similar behaviour and are therefore a potential driver for the observed variation. The mean intensity of the sub-daily rainfall extremes has also increased over the last 34 years. The sea surface temperature of the Danish waters is a strong candidate among the potential drivers for this increase, though the correlation between the two was not assessed directly in this study. Anthropogenic climate change will (and probably already has) influence both the sea surface temperature and the MSLP differences over the North Atlantic.

The PhD study has suggested and applied a spatio-temporal model for estimation of urban design intensities. The model has a threshold value that varies in both time and space, which eliminates the problem introduced by having an overweight of extreme events in one end of the observation period. Observations from rain gauges are, due to extent and movement of the meteorological systems, correlated in space. The correlation reduces the total amount of information in the dataset. The suggested model is capable of taking this correlation into account. The model cannot assess sampling uncertainty and compare it to the total amount of variability. This is an important feature of the regional models currently applied for estimation of design intensities. The study therefore suggests that the marginal models of the regional and temporal domain are evaluated before the full model is constructed.

Finally, the thesis has contributed to guidelines and frameworks for urban drainage engineers through discussions on how the new spatio-temporal model and the knowledge on drivers of temporal variability have affected/will influence urban design intensities in the past/future. Currently the model only includes time as temporal variable. Therefore, application outside the observation period is not recommended. However, the model can be modified to include physical explanatory variable like the sea surfaces temperatures or a given index for the MSLP, when their present and future influence is confirmed. Information from climate models is needed for projections of future extreme rainfall intensities. There is a high need for assessment and discussion of uncertainty, including the limitations of the climate models. The study suggests application of both standard and high climate factors in urban drainage design as a first step to address the uncertainty, but the future is dominated by unknown unknowns and the uncertainty will no matter what be underestimated. However, a simple case study based on different decision making frameworks show that the uncertainty of the future (whether dominated by natural fluctuations, anthropogenic climatic changes or both) is not a hindrance for adaptation.

7 Future research

This PhD study has provided a literature study on large scale drivers for variation of extreme rainfall in Denmark. Furthermore, initial analyses have been carried out indicating that relationships exist, e.g. between the number of extreme rainfall events and MSLP differences. However, the applied methodology should be improved, so that the inconvenient properties of the moving average method are avoided. A possible solution is either to apply another type of filter or to consider significant variability in all temporal domains, as in Lee and Ouarda (2010). As for an extended analysis of the variability over Denmark and the link to MSLP over the North Atlantic, the canonical correlation analysis applied by Haylock and Goodess (2004) appears to be a very promising option. Large scale drivers for the variation of extreme rainfall intensity have only been discussed on at superficial level. The analysis of long-term variations in the daily extreme rainfall intensity showed no trends, but the sub-daily rainfall extremes have increased since 1979. Basic time series analysis should be carried out to find potential large scale drivers of this increase. The SST of the Danish waters has increased since the 1980s and is a strong candidate, mainly because the variation in the intensity of the extreme events is driven by the availability of moisture that relates directly to temperature.

A better analysis of the temporal variability and the drivers behind will not remove the challenge of predicting future variability in the design rainfall. The interplay between the initial impacts of anthropogenic climate change and natural variability is likely to be important and will dominate the extreme rainfall in the decades to come. Climate change can, and likely will, alter the atmospheric circulation patterns. Probably, the overall global temperature change determines how critical this change will be. Further analyses are needed to show whether interaction already plays a role and is partly responsible for the increase over the last 34 years.

The ability of the climate models to reproduce the link between rainfall extremes and large scale drivers in Denmark is an important research topic, together with the future projection of the large scale drivers under different emission pathways. The climate models are also our only tool for understanding the interaction between anthropogenic climate change and natural variability.

With respect to the suggested statistical extreme value model for spatio-temporal variability, a better comparison with alternative models, like the non-stationary index flood model by Roth et al. (2012) and the max-stable theory (Thibaud et al. 2013; Westra and Sisson 2011) should be performed. The comparison could include an assessment of the underlying model assumptions and the uncertainty of the predicted design intensities.

9 References

Arnbjerg-Nielsen, K. (2011). Past, present, and future design of urban drainage systems with focus on Danish experiences. *Water Science and Technology*. **63**(3), 527-535.

Arnbjerg-Nielsen, K. and Fleischer, H.S. (2009). Feasible adaptation strategies for increased risk of flooding in cities due to climate change. *Water Science and Technology*. **60**(2), 273-281.

Aryal, S.K., Bates, B.C., Campbell, E.P., Li, Y., Palmer, M.J. and Viney, N.R. (2009). Characterizing and Modeling Temporal and Spatial Trends in Rainfall Extremes. *Journal of Hydrometeorology*. **10**(1), 241-253.

Austin, P.M. and Houze, R.A. (1972). Analysis of the structure of precipitation patterns in New England. *Journal of Applied Meteorology*. **11**(6), 926-935.

Berg, P., Moseley, C. and Haerter, J.O. (2013). Strong increase in convective precipitation in response to higher temperatures. *Nature Geoscience*. **6**(3), 181-185.

Burton, A., Kilsby, C.G., Fowler, H.J., Cowpertwait, P.S.P., O'Connell, P.E. (2008). RainSim: A spatial–temporal stochastic rainfall modelling system. *Environmental Modelling & Software*. **23**(12), 1356-1369.

Butler, D. and Davies, J.W. (2011). *Urban drainage*. Spon Press. London, UK

Cappelen, J. (2013). *Denmark - DMI Historical Climate Data Collection 1768-2012*. Technical report 13-02. Danish Meteorological Institute, Ministry of Climate and Energy. Copenhagen, Denmark.

Clarke, H. (2008) Classical decision rules and adaptation to climate change. *Australian Journal of Agricultural and Resource Economics*. **52**(4), 487–504.

Coles, S. (2001). *An introduction to statistical modeling of extreme values*. Springer. London, UK.

Cooley, D., Nychka, D. and Naveau, P. (2007). Bayesian spatial modeling of extreme precipitation return levels. *Journal of the American Statistical Association*. **102**(479), 824-840.

Dai, A. and Wigley, T.M.L. (2000). Global patterns of ENSO-induced precipitation. *Geophysical Research Letters*. **27**(9), 1283-1286.

Dai, A. (2013). The influence of the inter-decadal Pacific oscillation on US precipitation during 1923-2010. *Climate Dynamics*. **41**(3-4), 633-646.

Dingman, S.L. (1994). *Physical hydrology*. Prentice Hall Upper Saddle River. New Jersey, USA.

Dobson, A.J. (2002). *An introduction to generalized linear models*. Chapman & Hall/CRC. Boca Raton, Florida, U.S.

Dyrrdal, A.V., Lenkoski, A., Thorarinsdottir, T.L. and Stordal, F. (accepted). Bayesian hierarchical modeling of extreme hourly precipitation in Norway. *Environmetrics*.

Enfield, D.B., Mestas-Nunez, A.M. and Trimble, P.J. (2001). The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental US. *Geophysical Research Letters*. **28**(10), 2077-2080.

Faraway, J.J. (2006). *Extending the linear model with R: Generalized linear, mixed effects and nonparametric regression models*. Chapman and Hall/CRC. Boca Raton, Florida, U.S.

Folland, C.K., Knight, J., Linderholm, H.W., Fereday, D., Ineson, S. and Hurrell, J.W. (2009). The Summer North Atlantic Oscillation: Past, Present, and Future. *Journal of Climate*. **22**(5), 1082-1103.

Fowler, A.M. and Hennessy, K.J. (1995). Potential Impacts of Global Warming on the Frequency and Magnitude of Heavy Precipitation. *Natural Hazards*. **11**(3), 283-303.

Frich, P., Rosenørn, S., Madsen, H. and Jensen, J.J. (1998). *Observed Precipitation in Denmark, 1961-1990*. Technical report 97-8. Danish Meteorological Institute. Ministry of Transport. Denmark.

Ghosh, S. and Mallick, B.K. (2011). A hierarchical Bayesian spatio-temporal model for extreme precipitation events. *Environmetrics*. **22**(2), 192-204.

Gregersen, I.B., Sunyer Pinya, M.A., Madsen, H., Funder, S., Luchner, J., Rosbjerg, D. and Arnbjerg-Nielsen, K. (2014). *Past, present, and future variations of extreme precipitation in Denmark*. Technical report. DTU Environment, Kgs. Lyngby.

Halekoh, U., Hojsgaard, S. and Yan, J. (2006). The R Package geepack for Generalized Estimating Equations. *Journal of Statistical Software*. **15**(2), 1-11.

Hallegatte S., Hourcade J.C. and Ambrosi P. 2007. Using climate analogues for assessing climate change economic impacts in urban areas. *Climatic Change*. **82**(1-2), 47–60.

Hanel, M. and Buishand, T.A. (2010). On the value of hourly precipitation extremes in regional climate model simulations. *Journal of Hydrology*. **393**(3-4), 265-273.

Hardin, J.W. and Hilbe, J.M. (2003). *Generalized estimating equations*. Chapman & Hall/CRC, Boca Raton, Florida, U.S.

Harremoes, P., Gee, D., MacGarvin, M., Stirling, A., Keys, J., Wynne, B. and Vaz, S.G. (2002). *The precautionary principle in the 20th century : Late lessons from early warnings*. Earthscan Publications Ltd. London, UK.

Haylock, M.R. and Goodess, C.M. (2004). Interannual variability of european extreme winter rainfall and links with mean large-scale circulation. *International Journal of Climatology*. **24**(6), 759-776.

Heaton, M.J., Katzfuss, M., Ramachandar, S., Pedings, K., Gilleland, E., Mannshardt-Shamseldin, E. and Smith, R.L. (2011). Spatio-temporal models for large-scale indicators of extreme weather. *Environmetrics*. **22**(3), 294-303.

Hosking, J.R.M. (1990). L-moments: analysis and estimation of distributions using linear combinations of order statistics. *Journal of the Royal Statistical Society.Series B (Methodological)*. **52**(1), 105-124.

Hosking, J.R.M. and Wallis, J.R. (1993). Some Statistics Useful in Regional Frequency-Analysis. *Water Resources Research*. **29**(2), 271-281.

Hosking, J.R.M., Wallis, J.R. and Wood, E.F. (1985). An appraisal of the regional flood frequency procedures in the UK flood studies report. *Hydrological sciences journal*. **30**(1), 85-102.

Hurrell, J.W., Kushnir Y., Ottersen G. and Visbeck M. (2003). "An overview of the North Atlantic Oscillation." In (Eds.) Hurrell, J.W., Kushnir, Y., Ottersen, G. and Visbeck, M., *The North Atlantic Oscillation: Climatic Significance and Environmental Impacts*. American Geophysical Union. Washington, USA.

IPCC (2000). *Special Report Emission Scenarios*. Intergovernmental Panel on Climate Change. Cambridge University Press. Cambridge, UK.

IPCC (2013). (Eds.) Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley. *IPCC: Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA

Jones, P.D., Davies, T.D., Lister, D.H., Slonosky, V., Jonsson, T., Barring, L., Jonsson, P., Maheras, P., Kolyva-Machera, F., Barriendos, M., Martin-Vide, J., Rodriguez, R., Alcoforado, M.J., Wanner, H., Pfister, C., Luterbacher, J., Rickli, R., Schuepbach, E., Kaas, E., Schmith, T., Jacobeit, J. and Beck, C. (1999). Monthly mean pressure reconstructions for Europe for the 1780-1995 period. *International Journal of Climatology*. **19**(4), 347-364.

Jørgensen, H.K., Rosenørn, S., Madsen, H. and Mikkelsen, P.S. (1998). Quality control of rain data used for urban runoff systems. *Water Science and Technology*. **37**(11), 113-120.

Kendon, E.J., Roberts, N.M., Fowler, H.J., Roberts, M.J., Chan, S.C. and Senior, C.A. (2014). Heavier summer downpours with climate change revealed by weather forecast resolution model. *Nature Climate Change*. **4**(7), 570-576.

Kenyon, J. and Hegerl, G.C. (2010). Influence of Modes of Climate Variability on Global Precipitation Extremes. *Journal of Climate*. **23**(23), 6248-6262.

Kysely, J., Picek, J. and Beranova, R. (2010). Estimating extremes in climate change simulations using the peaks-over-threshold method with a non-stationary threshold. *Global and Planetary Change*. **72**(1-2), 55-68.

Larsen, A.N., Gregersen I.B., Christensen, O.B., Linde, J.J., Mikkelsen, P.S. (2009). Potential future increase in extreme one-hour precipitation events over Europe due to climate change. *Water Science and Technology*. **60**(9), 2205-2216

Lavers, D.A. and Villarini, G. (2013). The nexus between atmospheric rivers and extreme precipitation across Europe. *Geophysical Research Letters*. **40**(12), 3259-3264.

Lee, T. and Ouarda, T. (2010). Long-term prediction of precipitation and hydrologic extremes with nonstationary oscillation processes. *Journal of Geophysical Research-Atmospheres*. **115**(D13107).

Lenderink, G. and van Meijgaard, E. (2008). Increase in hourly precipitation extremes beyond expectations from temperature changes. *Nature Geoscience*. **1**(8), 511-514.

Lundholm, S.C. and Cappelen, J. (2010). *Ekstremnedbør i Danmark 1961-2010 - leverance til Koordineringsenhed for Forskning i klimaTilpasning (KFT)*. Technical report 10-17. Danish Meteorological Institute, Ministry of Climate and Energy. Copenhagen, Denmark.

Madsen, H., Arnbjerg-Nielsen, K. and Mikkelsen, P.S. (2009). Update of regional intensity-duration-frequency curves in Denmark: Tendency towards increased storm intensities. *Atmospheric Research*. **92**(3), 343-349.

Madsen, H., Gregersen, I.B. and Arnbjerg-Nielsen, K., (in prep.). Regional frequency analysis of short duration rainfall extremes in Denmark from 1979-2012. *Atmospheric Research*

Madsen, H., Mikkelsen, P.S., Rosbjerg, D. and Harremoes, P. (2002). Regional estimation of rainfall intensity-duration-frequency curves using generalized least squares regression of partial duration series statistics. *Water Resources Research*. **38**(11).

Madsen, H. and Rosbjerg, D. (1997). Generalized least squares and empirical Bayes estimation in regional partial duration series index-flood modeling. *Water Resources Research*. **33**(4), 771-781.

Mayer, S., Maule, C.F., Sobolowski, S., Christensen, O.B., Sørup, H.J.D., Sunyer, M. Arnbjerg-Nielsen, K. and Barstad, I. (accepted) Identifying added value in high-resolution climate simulations over Scandinavia. *Tellus A*.

Mikkelsen, P.S., Madsen, H., Rosbjerg, D. and Harremoes, P. (1996). Properties of extreme point rainfall .3. Identification of spatial inter-site correlation structure. *Atmospheric Research*. **40**(1), 77-98.

Molnar, P., Burlando, P. (2005). Preservation of rainfall properties in stochastic disaggregation by a simple random cascade model. *Atmospheric Research*. **77**(1-4), 137-151.

Nielsen, M.K. and Cappelen, J. (2006). *Drift af Spildvandskomitéens Regnmålersystem - Årsnotat 2005.* Technical report 06-03. Danish Meteorological Institute, Ministry of Climate and Energy. Copenhagen, Denmark.

Niemczynowicz, J. (1988). The Rainfall Movement - A Valuable Complement to Short-Term Rainfall Data. *Journal of Hydrology*. **104**(1-4), 311-326.

NOAA (2014a), El Niño – Southern Oscillation (ENSO), Online: http://www.cpc.ncep.noaa.gov/products/precip/CWlink/MJO/enso.shtml National Weather Service, National Oceanic and Atmospheric Administration, Mayland U.S., accessed September 2014.

NOAA (2014b), Northern Hemisphere Teleconnection Patterns, Online: http://www.cpc.ncep.noaa.gov/data/teledoc/telecontents.shtml National Weather Service, National Oceanic and Atmospheric Administration, Mayland U.S., accessed September 2013.

Ntegeka, V. and Willems, P. (2008). Trends and multidecadal oscillations in rainfall extremes, based on a more than 100-year time series of 10 min rainfall intensities at Uccle, Belgium. *Water Resources Research*. **44**(7).

Pedersen, A.N., Mikkelsen, P.S. and Arnbjerg-Nielsen, K. (2012). Climate change-induced impacts on urban flood risk influenced by concurrent hazards. *Journal of Flood Risk Management*. **5**(3), 203-214.

Rosbjerg, D., Madsen, H. and Rasmussen, P.F. (1992). Prediction in Partial Duration Series with Generalized Paretodistributed Exceedances. *Water Resources Research*. **28**(11), 3001-3010.

Renard, B. (2011). A Bayesian hierarchical approach to regional frequency analysis. *Water Resources Research*. **47**(11).

Roth, M., Buishand, T., Jongbloed, G., Tank, A. and van Zanten, J. (2012). A regional peaks-over-threshold model in a nonstationary climate. *Water Resources Research*. **48**(11).

Sang, H. and Gelfand, A.E. (2009). Hierarchical modeling for extreme values observed over space and time. *Environmental and ecological statistics*. **16**(3), 407-426.

Scaife, A.A., Folland, C.K., Alexander, L.V., Moberg, A. and Knight, J.R. (2008). European climate extremes and the North Atlantic Oscillation. *Journal of Climate*. **21**(1), 72-83.

Sørup, H.J.D., Christensen, O.B., Arnbjerg-Nielsen, K. and Mikkelsen P.S. (submitted) Downscaling future precipitation extremes to urban hydrology scales using a spatio-temporal Neyman-Scott weather generator. *Hydrology and Earth System Science Discussions*.

Shumway, R.H. and Stoffer, D.S. (2010). *Time series analysis and its applications*. Springer Science+ Business Media.

Stedinger, J.R. and Tasker, G.D. (1985). Regional Hydrologic Analysis .1. Ordinary, Weighted, and Generalized Least-Squares Compared. *Water Resources Research*. **21**(9), 1421-1432.

Sun, X., Thyer, M., Renard, B. and Lang, M. (2014). A general regional frequency analysis framework for quantifying local-scale climate effects: A case study of ENSO effects on Southeast Queensland rainfall. *Journal of Hydrology*. **512**, 53-68.

Sunyer, M.A., Madsen, H., Rosbjerg, D. and Arnbjerg-Nielsen, K. (2013). Regional interdependency of precipitation indices across Denmark in two ensembles of high-resolution RCMs. *Journal of Climate*. **26**(20), 7912-7928.

Sunyer, M.A., Madsen, H., Rosbjerg, D. and Arnbjerg-Nielsen, K. (2014). A Bayesian approach for uncertainty quantification of extreme precipitation projections including climate model interdependency and nonstationary bias. *Journal of Climate*. **27**(18), 7113-7132.

Trenberth, K.E., Dai, A., Rasmussen, R.M. and Parsons, D.B. (2003). The changing character of precipitation. *Bulletin of the American meteorological society*. **84**(9).

Thibaud, E., Mutzner, R. and Davison, A. (2013). Threshold modeling of extreme spatial rainfall. *Water Resources Research*. **49(**8), 4633-4644.

van der Linden, P., Mitchell, J.F.B. (Eds). (2009). *ENSEMBLES: Climate Change and its Impacts: Summary of research and results from the ENSEMBLES project*. Met Office Hadley Center. Exeter, UK.

van Vuuren, D.P., Edmonds, J., Kainuma, M., Riahi, K., Thomson, A., Hibbard, K., Hurtt, G.C., Kram, T., Krey, V., Lamarque, J.F., Masui, T., Meinshausen, M., Nakicenovic, N., Smith, S.J. and Rose, S.K. (2011). The representative concentration pathways: an overview. *Climatic Change*. **109**(1-2), 5-31.

Westra, S., Fowler, H.J., Evans, J.P., Alexander, L.V., Berg, P., Johnson, F., Kendon, E.J., Lenderink, G. and Roberts, N.M. (2014). Future changes to the intensity and frequency of short-duration extreme rainfall. *Reviews of Geophysics*. **52**(3), 522-555.

Westra, S. and Sisson, S.A. (2011). Detection of non-stationarity in precipitation extremes using a max-stable process model. *Journal of Hydrology*. **406**(1-2), 119-128.

Willems, P. (2013a). Multidecadal oscillatory behaviour of rainfall extremes in Europe. *Climatic Change*. **120**(4), 931-944.

Willems, P. (2013b). Adjustment of extreme rainfall statistics accounting for multidecadal climate oscillations. *Journal of Hydrology*. **490**, 126-133.

Willems, P., Olsson, J., Arnbjerg-Nielsen, K., Beecham, S., Pathirana, A., Gregersen, I.B., Madsen, H. and Nguyen, V.T.V. (2012). *Impacts of Climate Change on Rainfall Extremes and Urban Drainage Systems*. IWA Publishing Company.

Winther, L., Linde, J.J., Jensen, T.H., Mathiasen, L.L. and Johansen, N.B. (2006). *Afløbsteknik*. Polyteknisk forlag.

WPC (1949). Rastrup, J.A.C., Kaiser, E.W. and Rehof, K. *Fysisk, kemisk, hydrometrisk og biologisk Undersøgelse af Mølleaaen fra Lyngby Sø til Øresund 1946-1947, skrift nr. 1*. The Water Pollution Committee of the Society of Danish Engineers.
Available online (downloaded October 2014):
http://ida.dk/sites/prod.ida.dk/files/01UndersøgelseafMølleaaenfraLyngbySøtilØresund.pdf

WPC (1950). Eriksen, P.H. and Larsen, E. *Bearbejdelse af diagrammer fra de af Stads- og Havneingeniørforeningen opstillede selvregistrerende regnmålere for årene 1933-47, skrift nr. 2*. The Water Pollution Committee of the Society of Danish Engineers. Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/02Diagrammerfrastadsoghavneingeniørforeningen.pdf

WPC (1953). Rehof, K., Bretting, A.E., Christensen, W., Engel, E.E., Eriksen, P.H., Grimstrup, A.P., Paludan, A., Rendsvig, P.H. and Rastrup, J.A.C. *Bestemmelse af regnrækker, skrift nr. 6*. The Water Pollution Committee of the Society of Danish Engineers. Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/06Bestemmelseafregnrækker.pdf

WPC (1974). Eriksen, P.H., Rendsvig, P.H. and Skadhauge, A. *Bestemmelse af regnrækker, skrift nr. 16*. The Water Pollution Committee of the Society of Danish Engineers. Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/16Bestemmelseafregnrækker.pdf

WPC (1984). Jensen, M., Rattenborg, M. Prisum, M. and Poulsen, P. *Maksimalafstrømning og bassinvoluminer fra historiske regnserier, skrift nr. 18*. The Water Pollution Committee of the Society of Danish Engineers , Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/Skrift18udenbilag.pdf

WPC (1999). Mikkelsen, P.S, Madsen, H., Arnbjerg-Nielsen, K., Jørgensen, H.K., Rosbjerg, D. and Harremoës, P. *Regional variation af ekstremregn i Danmark, skrift nr. 26*. The Water Pollution Committee of the Society of Danish Engineers. Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/26RegionalvariationafekstremregniDanmark.pdf

WPC (2005). Harremoës, P., Pedersen, C.M, Laustsen, A., Sørensen, S., Laden, B., Friis, K., Andersen, A.K., Linde, J.J., Mikkelsen, P.S. and Jakobsen, C. *Funktionspraksis for afløbssystemer under regn, skrift nr. 27*. The Water Pollution Committee of the Society of Danish Engineers. Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/Skrift27Funktionspraksisforafløbssystemerunderregn.pdf

WPC (2006). Arnbjerg-Nielsen, K., Madsen, H. and Mikkelsen P.S. *Regional variation af ekstremregn i Danmark – ny bearbejdning 1979-2005, skrift nr. 28*. The Water Pollution Committee of the Society of Danish Engineers. Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/SVKskriftnr28.pdf

WPC (2008). Arnbjerg-Nielsen, K. *Forventede ændringer i ekstremregn som følge af klimaændringer, skrift nr. 29*. The Water Pollution Committee of the Society of Danish Engineers. Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/SVK_Skrift29_final.pdf

WPC (2014). Gregersen, I.B., Madsen, H., Linde, J.J. and Arnbjerg-Nielsen, K.. *Opdaterede klimafaktorer og dimensionsgivende regnintensiteter, skrift nr. 30*. The Water Pollution Committee of the Society of Danish Engineers. Available online (downloaded May 2014): http://ida.dk/sites/prod.ida.dk/files/svk_skrift30_0.pdf

Åström, H., Friis Hansen, P., Garré, L., and Arnbjerg-Nielsen, K. (2014). An influence diagram for urban flood risk assessment through pluvial flood hazards under non-stationary conditions. *Journal of Water and Climate Change*. **5**(3), 276-286.

10 Papers

I **Gregersen, I.B**. and Arnbjerg-Nielsen, K. (2012). Decision strategies for handling the uncertainty of future extreme rainfall under the influence of climate change. *Water Science and Technology* **66**(2), 284-291.

II **Gregersen, I.B.,** Sørup, H. J. D., Madsen, H., Rosbjerg, D., Mikkelsen, P. S. and Arnbjerg-Nielsen, K. (2013). Assessing future climatic changes of rainfall extremes at small spatio-temporal scales. *Climatic Change* **118**(3-4), 783-797.

III **Gregersen, I.B.,** Madsen, H., Rosbjerg, D., and Arnbjerg-Nielsen, K. (2013). A spatial and nonstationary model for the frequency of extreme rainfall events. *Water Resources Research* **49**(1), 127-136.

IV Sunyer, M.A., **Gregersen, I.B.**, Madsen, H., Luchner, J., Rosbjerg, D. and Arnbjerg-Nielsen, K. (2014). Comparison of different statistical downscaling methods to estimate changes in hourly extreme precipitation using RCM projections from ENSEMBLES. *International Journal of Climatology*. DOI: 10.1002/joc.4138

V **Gregersen, I.B.,** Madsen, H., Rosbjerg, D. and Arnbjerg-Nielsen, K. (2014). Long term variations of extreme rainfall in Denmark and Southern Sweden. *Climate Dynamics*. DOI: 10.1007/s00382-014-2276-4

VI **Gregersen, I.B.**, Madsen, H., Rosbjerg, D., and Arnbjerg-Nielsen, K. (in prep). A spatial and nonstationary model for Partial Duration Series of rainfall extremes. Manuscript in preparation for *Water Resources Research*

In this online version of the thesis, the papers are not included but can be obtained from electronic article databases e.g. via www.orbit.dtu.dk or on request from.

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The Department of Environmental Engineering (DTU Environment) conducts science-based engineering research within four sections:
Water Resources Engineering, Urban Water Engineering,
Residual Resource Engineering and Environmental Chemistry & Microbiology.

The department dates back to 1865, when Ludvig August Colding, the founder of the department, gave the first lecture on sanitary engineering as response to the cholera epidemics in Copenhagen in the late 1800s.

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